

7. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the net greenhouse gas flux resulting from the uses and changes in land types and forests in the United States.²⁰⁴ The Intergovernmental Panel on Climate Change 2006 *Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between certain land-use types termed forest land, cropland, grassland, and settlements (as well as wetlands). The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported using estimates of changes in forest carbon (C) stocks, non-carbon dioxide (CO₂) emissions from forest fires, and the application of synthetic fertilizers to forest soils. The greenhouse gas flux from agricultural lands (i.e., cropland and grassland) that is reported in this chapter includes changes in organic C stocks in mineral and organic soils due to land use and management, and emissions of CO₂ due to the application of crushed limestone and dolomite to managed land (i.e., soil liming) and urea fertilization. Fluxes are reported for four agricultural land use/land-use change categories: *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. Fluxes resulting from *Settlements Remaining Settlements* include those from urban trees and soil fertilization. Landfilled yard trimmings and food scraps are accounted for separately under *Other*.

The estimates in this chapter, with the exception of CO₂ fluxes from wood products and urban trees, and CO₂ emissions from liming and urea fertilization, are based on activity data collected at multiple-year intervals, which are in the form of forest, land-use, and municipal solid waste surveys. Carbon dioxide fluxes from forest C stocks (except the wood product components) and from agricultural soils (except the liming component) are calculated on an average annual basis from data collected in intervals ranging from 1 to 10 years. The resulting annual averages are applied to years between surveys. Calculations of non-CO₂ emissions from forest fires are based on forest CO₂ flux data. For the landfilled yard trimmings and food scraps source, periodic solid waste survey data were interpolated so that annual storage estimates could be derived. This flux has been applied to the entire time series, and periodic U.S. census data on changes in urban area have been used to develop annual estimates of CO₂ flux.

Land use, land-use change, and forestry activities in 2011 resulted in a net C sequestration of 905.0 Tg CO₂ Eq. (246.8 Tg C) (Table 7-1 and Table 7-2). This represents an offset of approximately 13.5 percent of total U.S. CO₂ emissions. Total land use, land-use change, and forestry net C sequestration increased by approximately 13.9 percent between 1990 and 2011.²⁰⁵ This increase was primarily due to an increase in the rate of net C accumulation in forest C stocks. Net C accumulation in *Forest Land Remaining Forest Land*, *Land Converted to Grassland*, and *Settlements Remaining Settlements* increased, while net C accumulation in *Cropland Remaining Cropland*, *Grassland Remaining Grassland*, and landfilled yard trimmings and food scraps slowed over this period. Emissions from *Land Converted to Cropland* decreased between 1990 and 2011.

²⁰⁴ The term “flux” is used here to encompass both emissions of greenhouse gases to the atmosphere, and removal of C from the atmosphere. Removal of C from the atmosphere is also referred to as “carbon sequestration.”

²⁰⁵ Carbon sequestration estimates are net figures. The C stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the C stock decreases, and the pool acts as a source. When gains exceed losses, the C stock increases, and the pool acts as a sink; also referred to as net C sequestration.

Table 7-1: Net CO₂ Flux from Carbon Stock Changes in Land Use, Land-Use Change, and Forestry

Sink Category	1990	2005	2007	2008	2009	2010	2011
Forest Land Remaining Forest Land ^a	(696.8)	(905.0)	(859.3)	(833.3)	(811.3)	(817.6)	(833.5)
Cropland Remaining Cropland	(34.1)	(20.3)	(6.6)	(5.2)	(4.6)	(3.0)	(2.9)
Land Converted to Cropland	21.0	13.5	14.5	14.5	14.5	14.5	14.5
Grassland Remaining Grassland	(5.3)	(1.0)	7.1	7.2	7.3	7.3	7.4
Land Converted to Grassland	(7.7)	(10.2)	(9.0)	(9.0)	(8.9)	(8.8)	(8.8)
Settlements Remaining Settlements ^b	(47.5)	(63.2)	(65.0)	(66.0)	(66.9)	(67.9)	(68.8)
Other (Landfilled Yard Trimmings and	(24.2)	(11.6)	(10.9)	(10.9)	(12.7)	(13.3)	(13.0)
Total	(794.5)	(997.8)	(929.2)	(902.6)	(882.6)	(888.8)	(905.0)

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

^a Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

^b Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

Table 7-2: Net CO₂ Flux from Carbon Stock Changes in Land Use, Land-Use Change, and Forestry

Sink Category	1990	2005	2007	2008	2009	2010	2011
Forest Land Remaining Forest Land ^a	(190.0)	(246.8)	(234.4)	(227.3)	(221.3)	(223.0)	(227.3)
Cropland Remaining Cropland	(9.3)	(5.5)	(1.8)	(1.4)	(1.2)	(0.8)	(0.8)
Land Converted to Cropland	5.7	3.7	4.0	4.0	4.0	4.0	4.0
Grassland Remaining Grassland	(1.4)	(0.3)	1.9	2.0	2.0	2.0	2.0
Land Converted to Grassland	(2.1)	(2.8)	(2.5)	(2.4)	(2.4)	(2.4)	(2.4)
Settlements Remaining Settlements ^b	(13.0)	(17.2)	(17.7)	(18.0)	(18.3)	(18.5)	(18.8)
Other (Landfilled Yard Trimmings and	(6.6)	(3.2)	(3.0)	(3.0)	(3.5)	(3.6)	(3.6)
Total	(216.7)	(272.1)	(253.4)	(246.2)	(240.7)	(242.4)	(246.8)

Note: 1 Tg C = 1 teragram C = 1 million metric tons C. Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

^a Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

^b Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

Emissions from Land Use, Land-Use Change, and Forestry are shown in Table 7-3 and Table 7-4. Liming of agricultural soils and urea fertilization in 2011 resulted in CO₂ emissions of 8.1 Tg CO₂ Eq. (8,117 Gg). Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO₂ emissions of .9 Tg CO₂ Eq. (918 Gg), and nitrous oxide (N₂O) emissions of less than 0.05 Tg CO₂ Eq. The application of synthetic fertilizers to forest soils in 2011 resulted in direct N₂O emissions of 0.4 Tg CO₂ Eq. (1 Gg). Direct N₂O emissions from fertilizer application to forest soils have increased by 455 percent since 1990, but still account for a relatively small portion of overall emissions. Additionally, direct N₂O emissions from fertilizer application to settlement soils in 2011 accounted for 1.5 Tg CO₂ Eq. (4 Gg). This represents an increase of 50 percent since 1990. Forest fires in 2011 resulted in methane (CH₄) emissions of 14.2 Tg CO₂ Eq. (675 Gg), and in N₂O emissions of 11.6 Tg CO₂ Eq. (37 Gg).

Table 7-3: Emissions from Land Use, Land-Use Change, and Forestry (Tg CO₂ Eq.)

Source Category	1990	2005	2007	2008	2009	2010	2011
CO₂	8.1	8.9	9.2	9.6	8.3	9.4	9.0
Cropland Remaining Cropland:							
Liming of Agricultural Soils	4.7	4.3	4.5	5.0	3.7	4.7	4.5
Cropland Remaining Cropland							
Urea Fertilization	2.4	3.5	3.8	3.6	3.6	3.7	3.7
Wetlands Remaining Wetlands:							
Peatlands Remaining Peatlands	1.0	1.1	1.0	1.0	1.1	1.0	0.9
CH₄	2.5	8.0	14.4	8.7	5.7	4.7	14.2
Forest Land Remaining Forest	2.5	8.0	14.4	8.7	5.7	4.7	14.2

Land: Forest Fires							
N ₂ O	3.1	8.4	13.7	8.9	6.4	5.6	13.4
Forest Land Remaining Forest							
Land: Forest Fires	2.0	6.6	11.7	7.1	4.7	3.8	11.6
Forest Land Remaining Forest							
Land: Forest Soils ^a	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Settlements Remaining							
Settlements: Settlement Soils ^b	1.0	1.5	1.6	1.5	1.4	1.5	1.5
Wetlands Remaining Wetlands:							
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Total	13.7	25.4	37.3	27.2	20.4	19.7	36.6

+ Less than 0.05 Tg CO₂ Eq.

Note: These estimates include direct emissions only. Indirect N₂O emissions are reported in the Agriculture chapter. Totals may not sum due to independent rounding.

^a Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

^b Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion

Table 7-4: Emissions from Land Use, Land-Use Change, and Forestry (Gg)

Source Category	1990	2005	2007	2008	2009	2010	2011
CO₂	8,117	8,933	9,233	9,630	8,325	9,361	9,034
Cropland Remaining Cropland:							
Liming of Agricultural Soils	4,667	4,349	4,464	5,025	3,669	4,688	4,454
Cropland Remaining Cropland							
Urea Fertilization	2,417	3,504	3,757	3,613	3,567	3,663	3,663
Wetlands Remaining Wetlands:							
Peatlands Remaining Peatlands	1,033	1,079	1,012	992	1,089	1,010	918
CH₄	118	383	684	413	271	222	675
Forest Land Remaining Forest							
Land: Forest Fires	118	383	684	413	271	222	675
N₂O	10	27	44	29	21	18	43
Forest Land Remaining Forest							
Land: Forest Fires	7	21	38	23	15	12	37
Forest Land Remaining Forest							
Land: Forest Soils ^a	0	1	1	1	1	1	1
Settlements Remaining							
Settlements: Settlement Soils ^b	3	5	5	5	5	5	5
Wetlands Remaining Wetlands:							
Peatlands Remaining Peatlands	0	0	0	0	0	0	0

+ Emissions are less than 0.5 Tg CO₂ Eq.

Note: These estimates include direct emissions only. Indirect N₂O emissions are reported in the Agriculture chapter. Totals may not sum due to independent rounding.

^a Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land*, and *Land Converted to Forest Land*, but not from land-use conversion.

^b Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements*, and *Land Converted to Settlements*, but not from land-use conversion.

Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emissions inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC).²⁰⁶ Additionally, the calculated emissions and sinks in a given year for the United States are presented in a

²⁰⁶ See <<http://www.ipcc-nggip.iges.or.jp/public/index.html>>.

common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.²⁰⁷ The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this inventory report are comparable to emissions and sinks reported by other countries. Emissions and sinks provided in this inventory do not preclude alternative examinations, but rather this inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

7.1 Representation of the U.S. Land Base

A national land-use categorization system that is consistent and complete both temporally and spatially is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country, (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series (i.e., such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories unless the national land base is changing), and (3) account for greenhouse gas fluxes on all managed lands. The implementation of such a system helps to ensure that estimates of greenhouse gas fluxes are as accurate as possible. This section of the Inventory has been developed in order to comply with this guidance.

Multiple databases are used to track land management in the United States, which are also used as the basis to classify U.S. land area into the six IPCC land-use categories (i.e., *Forest Land Remaining Forest Land*, *Cropland Remaining Cropland*, *Grassland Remaining Grassland*, *Wetlands Remaining Wetlands*, *Settlements Remaining Settlements* and *Other Land Remaining Other Land*) and the thirty land-use change categories (e.g., *Cropland Converted to Forest Land*, *Grassland Converted to Forest Land*, *Wetlands Converted to Forest Land*, *Settlements Converted to Forest Land*, *Other Land Converted to Forest Lands*)²⁰⁸ (IPCC 2006). The primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI)²⁰⁹ and the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)²¹⁰ Database. The U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD)²¹¹ is also used to identify land uses in regions that were not included in the NRI or FIA.

The total land area included in the U.S. Inventory is 936 million hectares. Approximately 867 million hectares of this land base is considered managed, which has basically not changed over the time series of the Inventory (Table 7-5).²¹² In 2011, the United States had a total of 301 million hectares of managed Forest Land (4 percent increase since 1990), 159 million hectares of Cropland (6.6 percent decrease since 1990), 294 million hectares of managed Grassland (3.4 percent decrease since 1990), 43 million hectares of managed Wetlands (3.4 percent decrease since 1990), 51 million hectares of Settlements (31 percent increase since 1990), and 19 million hectares of managed Other Land (Table 7-6). Wetlands are not differentiated between managed and unmanaged and are reported as managed, although some wetlands would be unmanaged according to the U.S. definition (see definition later in this section). Future improvements will include a differentiation between managed and unmanaged wetlands. In addition, C stock changes are not currently estimated for the entire land base, which leads to discrepancies between

²⁰⁷ See <http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/5270.php>.

²⁰⁸ Land-use category definitions are provided in the Methodology section.

²⁰⁹ NRI data is available at <<http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>>.

²¹⁰ FIA data is available at <<http://www.fia.fs.fed.us/tools-data/default.asp>>.

²¹¹ NLCD data is available at <<http://www.mrlc.gov/>>.

²¹² The current land representation does not include areas from U.S. territories, but there are planned improvements to include these regions in future reports

the area data presented here and in the subsequent sections of the NRI. Planned improvements are underway or in development phases to conduct an inventory of C stock changes on all managed land (e.g., federal grasslands).

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement patterns, although all land-uses occur within each of the fifty states (Figure 7-1). Forest Land tends to be more common in the eastern states, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and Grassland is more common in the western United States. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper Midwest and eastern portions of the country. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 7-5: Managed and Unmanaged Land Area by Land Use Categories (thousands of hectares)

Land Use Categories	1990	2005	2007	2008	2009	2010	2011
Managed Lands	866,933	866,932	866,932	866,932	866,932	866,932	866,932
Forest	290,080	297,543	298,783	299,355	299,928	300,500	301,073
Croplands	170,309	159,946	159,101	159,096	159,091	159,087	159,083
Grasslands	304,636	297,122	295,930	295,528	295,126	294,722	294,319
Settlements	38,675	49,660	50,620	50,617	50,614	50,611	50,608
Wetlands	44,409	43,816	43,498	43,351	43,203	43,056	42,909
Other	18,824	18,844	19,000	18,985	18,970	18,955	18,941
Unmanaged Lands	69,498	69,499	69,499	69,499	69,499	69,499	69,499
Forest	14,565	14,565	14,565	14,565	14,565	14,565	14,565
Croplands	0	0	0	0	0	0	0
Grasslands	39,675	39,676	39,676	39,676	39,676	39,676	39,676
Settlements	0	0	0	0	0	0	0
Wetlands	0	0	0	0	0	0	0
Other	15,258	15,259	15,259	15,259	15,259	15,259	15,259
Total	936,431	936,431	936,431	936,431	936,431	936,431	936,431

Table 7-6: Land Use and Land-Use Change for the U.S. Managed Land Base (thousands of hectares)

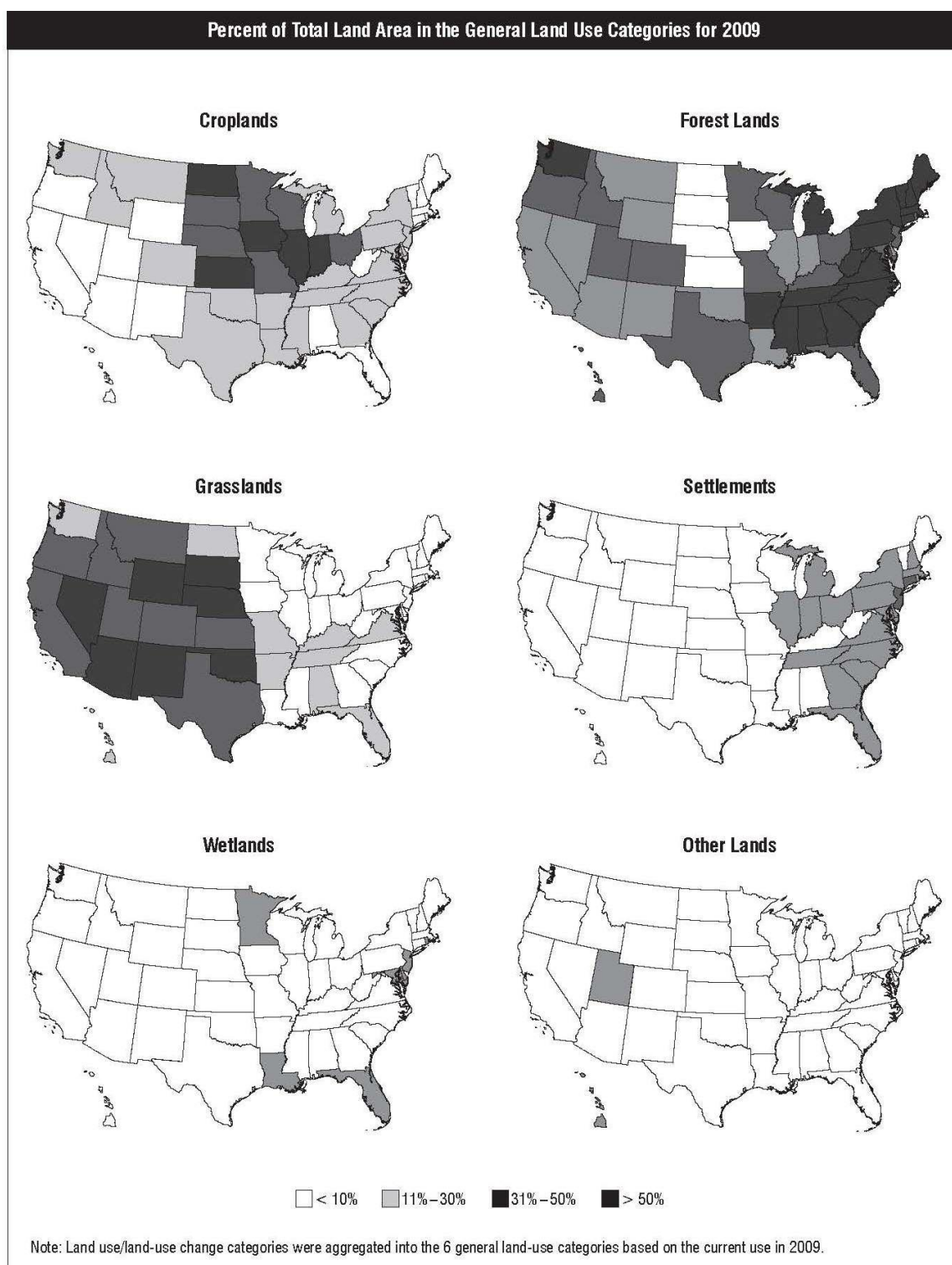
Land Use & Land-Use Change Categories ^a	1990	2005	2007	2008	2009	2010	2011
Total Forest Land	290,080	297,543	298,783	299,355	299,928	300,500	301,073
FF	284,970	285,250	287,311	287,877	288,444	289,010	289,577
CF	1,118	2,651	2,444	2,444	2,444	2,445	2,445
GF	3,425	7,821	7,297	7,298	7,300	7,302	7,303
WF	66	255	262	262	263	264	265
SF	103	371	386	386	387	388	389
OF	398	1,194	1,084	1,087	1,089	1,092	1,094
Total Cropland	170,309	159,946	159,101	159,096	159,091	159,087	159,083
CC	154,842	143,069	143,879	143,874	143,870	143,866	143,863
FC	1,118	675	568	568	568	568	568
GC	13,583	15,067	13,581	13,580	13,580	13,580	13,580
WC	156	193	174	174	174	174	174
SC	431	688	669	669	669	669	669
OC	180	253	231	231	231	231	231
Total Grassland	304,636	297,122	295,930	295,528	295,126	294,722	294,319
GG	294,417	277,981	278,134	277,803	277,471	277,138	276,805
FG	1,611	2,990	2,725	2,723	2,721	2,719	2,717
CG	7,909	14,625	13,643	13,575	13,507	13,439	13,370

WG	238	408	329	329	328	328	328
SG	111	274	267	267	267	267	267
OG	349	844	832	832	831	831	831
Total Wetlands	44,409	43,816	43,498	43,351	43,203	43,056	42,909
WW	43,760	42,309	42,061	41,917	41,772	41,628	41,483
FW	140	393	382	380	378	376	374
CW	132	365	345	345	345	344	344
GW	343	696	662	661	661	661	661
SW	0	10	10	10	10	10	10
OW	33	43	39	38	38	38	37
Total Settlements	38,675	49,660	50,620	50,617	50,614	50,611	50,608
SS	34,134	35,265	36,345	36,342	36,339	36,336	36,333
FS	1,787	6,111	6,089	6,089	6,089	6,089	6,089
CS	1,343	3,625	3,518	3,518	3,518	3,518	3,518
GS	1,353	4,430	4,436	4,436	4,436	4,436	4,436
WS	3	31	30	30	30	30	30
OS	55	198	201	201	201	201	201
Total Other Land	18,824	18,844	19,000	18,985	18,970	18,955	18,941
OO	17,791	16,625	16,710	16,695	16,681	16,666	16,652
FO	182	538	570	569	569	569	569
CO	331	645	703	703	703	703	703
GO	454	896	895	895	895	894	894
WO	63	119	102	102	102	102	102
SO	2	21	20	20	20	20	20
Grand Total	866,933	866,932	866,932	866,932	866,932	866,932	866,932

^aThe abbreviations are “F” for Forest Land, “C” for Cropland, “G” for Grassland, “W” for Wetlands, “S” for Settlements, and “O” for Other Lands. Lands remaining in the same land use category are identified with the land use abbreviation given twice (e.g., “FF” is Forest Land Remaining Forest Land), and land use change categories are identified with the previous land use abbreviation followed by the new land use abbreviation (e.g., “CF” is Cropland Converted to Forest Land).

Notes: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for wetlands which includes both managed and unmanaged lands based on the definitions for the current U.S. Land Representation Assessment. In addition, U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See Planned Improvements for discussion on plans to include territories in future Inventories.

Figure 7-1. Percent of Total Land Area in the General Land-Use Categories for 2011



Methodology

IPCC Approaches for Representing Land Areas

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land-use category, but does not provide detailed information on changes of area between categories and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., Forest Land to Cropland, Cropland to Forest Land, Grassland to Cropland, etc.), using surveys or other forms of data that do not provide location data on specific parcels of land. Approach 3 extends Approach 2 by providing location data on specific parcels of land, such as maps, along with the land-use history. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. All of these datasets have a spatially-explicit time series of land-use data, and therefore Approach 3 is used to provide a full representation of land use in the U.S. Inventory. Lands are treated as remaining in the same category (e.g., *Cropland Remaining Cropland*) if a land-use change has not occurred in the last 20 years. Otherwise, the land is classified in a land-use-change category based on the current use and most recent use before conversion to the current use (e.g., *Cropland Converted to Forest Land*).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The U.S. definitions of managed and unmanaged lands are similar to the basic IPCC (2006) definition of managed land, but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community or societal objectives where these areas are readily accessible to society.²¹³
- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to society due to the remoteness of the locations. Though these lands may be influenced indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO₂ fertilization, they are not influenced by a direct human intervention.²¹⁴

²¹³ Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands is difficult due to limited data availability. Wetlands are not characterized by use within the NRI. Therefore, unless wetlands are managed for cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. As a result, all wetlands are reported as managed. See the Planned Improvements section of the Inventory for work being done to refine the Wetland area estimates.

²¹⁴ There will be some areas that qualify as Forest Land or Grassland according to the land use criteria, but are classified as unmanaged land due to the remoteness of their location.

In addition, managed land that is converted to unmanaged remains in the managed land base for 20 years to account for legacy effects of management on C stocks.

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. In order to reflect U.S. circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of Forest Land is based on the FIA definition of forest,²¹⁵ while definitions of Cropland, Grassland, and Settlements are based on the NRI.²¹⁶ The definitions for Other Land and Wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 36.6 m wide and 0.4 ha in size with at least 10 percent cover (or equivalent stocking) by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Roadside, streamside, and shelterbelt strips of trees must have a crown width of at least 36.6 m and continuous length of at least 110.6 m to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 36.6 m wide or 0.4 ha in size; otherwise they are excluded from Forest Land and classified as Settlements. Tree-covered areas in agricultural production settings, such as fruit orchards, or tree-covered areas in urban settings, such as city parks, are not considered forest land (Smith et al. 2009).
- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest; this category includes both cultivated and non-cultivated lands.²¹⁷ Cultivated crops include row crops or close-grown crops and also hay or pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with alley cropping and windbreaks,²¹⁸ as well as lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides²¹⁹). Roads through Cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Cropland area estimates and are, instead, classified as Settlements.
- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing, and includes both pastures and native rangelands.²²⁰ This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Savannas, some wetlands and deserts, in addition to tundra are considered Grassland.²²¹ Woody plant communities of low forbs and shrubs, such as mesquite, chaparral, mountain shrub, and pinyon-juniper, are also classified as Grassland if they do not meet the criteria for Forest Land. Grassland includes land managed with agroforestry practices such as silvipasture and windbreaks, assuming the stand or woodlot does not meet the criteria for Forest Land. Roads through Grassland, including interstate highways, state highways, other paved roads, gravel roads,

²¹⁵ See <http://socrates.lv-hrc.nevada.edu/fia/ab/issues/pending/glossary/Glossary_5_30_06.pdf>.

²¹⁶ See <<http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>>.

²¹⁷ A minor portion of Cropland occurs on federal lands, and is not currently included in the C stock change inventory. A planned improvement is underway to include these areas in future C inventories.

²¹⁸ Currently, there is no data source to account for biomass C stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the cropland land base.

²¹⁹ A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees.

²²⁰ Grasslands on federal lands are included in the managed land base, but C stock changes are not estimated on these lands. Federal grassland areas have been assumed to have negligible changes in C due to limited land use and management change, but planned improvements are underway to further investigate this issue and include these areas in future C inventories.

²²¹ IPCC (2006) guidelines do not include provisions to separate desert and tundra as land categories.

dirt roads, and railroads are excluded from Grassland area estimates and are, instead, classified as Settlements.

- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year. Managed Wetlands are those where the water level is artificially changed, or were created by human activity. Certain areas that fall under the managed Wetlands definition are covered in other areas of the IPCC guidance and/or the inventory, including Cropland (e.g., rice cultivation), Grassland, and Forest Land (including drained or undrained forested wetlands).
- *Settlements*: A land-use category representing developed areas consisting of units of 0.25 acres (0.1 ha) or more that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are tracts of less than 10 acres (4.05 ha) that may meet the definitions for Forest Land, Cropland, Grassland, or Other Land but are completely surrounded by urban or built-up land, and so are included in the settlement category. Rural transportation corridors located within other land uses (e.g., Forest Land, Cropland, and Grassland) are also included in Settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories, which allows the total of identified land areas to match the managed land base.

Land-Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land-Use Data Sources

The three main data sources for land area and use data in the United States are the NRI, FIA, and the NLCD. For the Inventory, the NRI is the official source of data on all land uses on non-federal lands (except forest land), and is also used as the resource to determine the total land base for the conterminous United States and Hawaii. The NRI is conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160-acre [64.75 ha] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). The NRI survey utilizes data derived from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for croplands and grasslands, and is used as the basis to account for C stock changes in agricultural lands (except federal Grasslands). The NRI survey was conducted every 5 years between 1982 and 1997, but shifted to annualized data collection in 1998. This Inventory incorporates data through 2007 from the NRI.

The FIA program, conducted by the USFS, is the official source of data on Forest Land area and management data for the Inventory. FIA engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for phases are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial photographs or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate C stock changes for forest land. Historically, FIA inventory surveys had been conducted periodically, with all plots in a state being measured at a frequency of every 5 to 14 years. A new national plot design and annual sampling design was introduced by FIA about ten years ago. Most states, though, have only recently been brought into this system. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every 5 years. See Annex 3.12

to see the specific survey data available by state. The most recent year of available data varies state by state (range of most recent data is from 2002 through 2012).

Though NRI provides land-area data for both federal and non-federal lands, it only includes land-use data on non-federal lands, and FIA only records data for forest land.²²² Consequently, major gaps exist when the datasets are combined, such as federal grassland operated by the Bureau of Land Management (BLM), USDA, and National Park Service, as well as most of Alaska.²²³ The NLCD is used as a supplementary database to account for land use on federal lands that are not included in the NRI and FIA databases. The NLCD land-cover classification scheme, available for 1992, 2001, and 2006, has been applied over the conterminous United States (Homer et al. 2007), and also for Alaska and Hawaii in 2001. For the conterminous United States, the NLCD Land Cover Change Products for 2001 and 2006 were used in order to represent both land use and land-use change for federal lands (Fry et al. 2011, Homer et al. 2007). The NLCD products are based primarily on Landsat Thematic Mapper imagery. The NLCD contains 21 categories of land-cover information, which have been aggregated into the IPCC land-use categories, and the data are available at a spatial resolution of 30 meters. The federal land portion of the NLCD was extracted from the dataset using the federal land area boundary map from the National Atlas (U.S. Department of Interior 2005). This map represents federal land boundaries in 2005, so as part of the analysis, the federal land area was adjusted annually based on the NRI federal land area estimates (i.e., land is periodically transferred between federal and non-federal ownership). Consequently, the portion of the land base categorized with NLCD data varied from year to year, corresponding to an increase or decrease in the federal land base. The NLCD is strictly a source of land-cover information, however, and does not provide the necessary site conditions, crop types, and management information from which to estimate C stock changes on those lands.

Another step in the analysis is to address gaps as well as overlaps in the representation of the U.S. land base between the Agricultural Carbon Stock Inventory (*Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland*) and Forest Land Carbon Stock Inventory (*Forest Land Remaining Forest Land and Land Converted to Forest Land*), which are based on the NRI and FIA databases, respectively. NRI and FIA have different criteria for classifying forest land and sampling designs, leading to discrepancies in the resulting estimates of Forest Land area on non-federal land. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying Forest Land on federal lands. Moreover, dependence exists between the Forest Land area and the amount of land designated as other land uses in both the NRI and the NLCD, such as the amount of Grassland, Cropland, and Wetlands, relative to the Forest Land area. This results in inconsistencies among the three databases for estimated Forest Land area, as well as for the area estimates for other land-use categories. FIA is the main database for forest statistics, and consequently, the NRI and NLCD were adjusted to achieve consistency with FIA estimates of Forest Land. The adjustments were made at a state-scale, and it was assumed that the majority of the discrepancy in forest area was associated with an under- or over-prediction of Grassland and Wetland area in the NRI and NLCD due to differences in Forest Land definitions. Specifically, the Forest Land area for a given state according to the NRI and NLCD was adjusted to match the FIA estimates of Forest Land for non-federal and federal land, respectively. In a second step, corresponding increases or decreases were made in the area estimates of Grassland and Wetland from the NRI and NLCD, in order to balance the change in forest area, and therefore not change the overall amount of managed land within an individual state. The adjustments were based on the proportion of land within each of these land-use categories at the state-level. (i.e., a higher proportion of Grassland led to a larger adjustment in Grassland area).

As part of Quality Assurance /Quality Control (QA/QC), the land base derived from the NRI, FIA and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) survey (U.S. Census Bureau 2010). The U.S. Census Bureau gathers data on the U.S. population and economy, and has a database of land areas for the country. The land area estimates from the U.S. Census Bureau differ from those provided by the land-use surveys used in the Inventory because of discrepancies in the reporting approach for the census and the methods used in the NRI, FIA, and NLCD. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are derived from remote sensing data instead of the land survey approach used by the U.S. Census Survey.

²²² FIA does collect some data on non-forest land use, but these are held in regional databases versus the national database. The status of these data is being investigated.

²²³ The survey programs also do not include U.S. Territories with the exception of non-federal lands in Puerto Rico, which are included in the NRI survey. Furthermore, NLCD does not include coverage for U.S. Territories.

More importantly, the U.S. Census Survey does not provide a time series of land-use change data or land management information, which is critical for conducting emission inventories and is provided from the NRI and FIA surveys. Consequently, the U.S. Census Survey was not adopted as the official land area estimate for the Inventory. Rather, the NRI data were adopted because this database provides full coverage of land area and land use for the conterminous United States and Hawaii. Regardless, the total difference between the U.S. Census Survey and the NRI data is about 25 million hectares for the total conterminous U.S. land base of about 786 million hectares currently included in the Inventory, or a 3.1 percent difference. Much of this difference is associated with open waters in coastal regions and the Great Lakes. NRI does not include as much of the area of open waters in these regions as the U.S. Census Survey.

Managed Land Designation

Lands are designated as managed in the United States based on the definitions provided earlier in this section. In order to apply the definitions in an analysis of managed land, the following criteria are used:

- All croplands and settlements are designated as managed so only grassland, forest land or other lands may be designated as unmanaged land;²²⁴
- All forest lands with active fire protection are considered managed;
- All grasslands are considered managed at a county scale if there are livestock in the county;
- Other areas are considered managed if accessible based on the proximity to roads and other transportation corridors, and/or infrastructure; and
- Lands that were previously managed remain in the managed land base for 20 years following the conversion to account for legacy effects of management on C stocks.

These criteria will be expanded in the future as other data sources become available, such as national datasets on mining and resource extraction.

The analysis of managed lands is conducted using a geographic information system. Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011, Homer et al. 2007). Active fire management is determined from maps of federal and state management plans from the National Atlas (U.S. Department of Interior 2005) and Alaska Interagency Fire Management Council (1998). It is noteworthy that all federal lands in the conterminous U.S. have active fire protection, and are therefore designated as managed. The designation of grasslands as managed is determined based on USDA-NASS livestock population data at the county scale (U.S. Department of Agriculture 2011). Accessibility is evaluated based on a 10km buffer surrounding road and train transportation networks using the ESRI Data and Maps product (ESRI 2008), and a 10km buffer surrounding settlements using NLCD. The resulting managed land area is overlaid on the NLCD to estimate the area of managed land by land use for both federal and non-federal lands. The remaining land represents the unmanaged land base.

Approach for Combining Data Sources

The managed land base in the United States has been classified into the six IPCC land-use categories using definitions developed to meet national circumstances, while adhering to IPCC (2006).²²⁵ In practice, the land was initially classified into a variety of land-use categories using the NRI, FIA and NLCD, and then aggregated into the thirty-six broad land use and land-use-change categories identified in IPCC (2006). Details on the approach used to combine data sources for each land use are described below as are the gaps that will be reconciled as part of ongoing planned improvements:

- *Forest Land*: Both non-federal and federal forest lands in both the continental United States and coastal Alaska are covered by FIA. FIA is used as the basis for both Forest Land area data as well as to estimate C stocks and fluxes on Forest Land. Interior Alaska is not currently surveyed by FIA so forest land in Alaska

²²⁴ A planned improvement is underway to deal with an exception for wetlands which includes both managed and unmanaged lands based on the definitions for the current U.S. Land Representation Assessment.

²²⁵ Definitions are provided in the previous section.

is evaluated with 2001 NLCD. Forest Lands in U.S. territories are currently excluded from the analysis, but FIA surveys are currently being conducted on U.S. territories and will become available in the future. NRI is being used in the current report to provide Forest Land areas on non-federal lands in Hawaii. Currently, federal forest land in Hawaii is evaluated with the 2001 NLCD, but FIA data will be collected in Hawaii in the future.

- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Cropland area data as well as to estimate C stocks and fluxes on Cropland. NLCD 2001 is used to determine Cropland area in Alaska. Croplands in U.S. territories are excluded from both NRI data collection and the NLCD.
- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Grassland area data as well as to estimate C stocks and fluxes on Grassland. U.S. territories are excluded from both NRI data collection and the current release of the NLCD product. Grassland on federal Bureau of Land Management lands, Department of Defense lands, National Parks and within USFS lands are covered by the NLCD. In addition, federal and non-federal grasslands in Alaska are currently excluded from the analysis, but NLCD has a new product for Alaska that will be incorporated into the assessment for future reports.
- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while federal wetlands and wetlands in Alaska are covered by the NLCD. U.S. territories are excluded. This currently includes both managed and unmanaged wetlands as no database has yet been applied to make this distinction. See Planned Improvements for details.
- *Settlements*: The NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of Forest Land or Grassland under 10 acres (4.05 ha) are contained within settlements or urban areas, they are classified as Settlements (urban) in the NRI database. If these parcels exceed the 10 acre (4.05 ha) threshold and are Grassland, they will be classified as such by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Settlements on federal lands and in Alaska are covered by NLCD. Settlements in U.S. territories are currently excluded from NRI and NLCD.
- *Other Land*: Any land not falling into the other five land categories and, therefore, categorized as Other Land is classified using the NRI for non-federal areas in the 49 states (excluding Alaska) and NLCD for the federal lands and Alaska. Other land in U.S. territories is excluded from the NLCD.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is initiated by distinguishing between managed and unmanaged lands. The managed lands are then assigned, from highest to lowest priority, in the following manner:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as Grassland, Forest Land, Wetlands, and Cropland, respectively, but when located in close proximity to settlement areas they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the Settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage or fiber. The consequence of this ranking is that crops in rotation with grass will be classified as Cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as Cropland, even though these areas may meet the definitions of Grassland or Forest Land, respectively. Similarly, Wetlands are considered Croplands if they are used for crop production, such as rice or cranberries. Forest Land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands and Other Land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a single land use. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a Wetland is classified as Forest Land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, Wetlands are classified as Cropland if they are used for crop production, such as rice or cranberries. In either case, emissions from Wetlands are included in the Inventory if human interventions are influencing emissions from Wetlands, in accordance with the guidance provided in IPCC (2006).

Recalculations Discussion

Alaska was added to the latest inventory and a formal analysis was conducted for managed and unmanaged lands. Both improvements led to significant changes in the reporting of the managed land base. Overall more land area is incorporated into this Inventory, but a large portion of this land is designated as unmanaged due to the remoteness of some areas in Alaska.

In addition, new data were incorporated from FIA on forestland areas, which was used to make minor adjustments to the time series. FIA conducts a survey of plots annually so that each plot is visited every 5 years (Note: some states have not initiated the annual sampling regime, as discussed previously). Consequently, the time series is updated each year as new data are collected over the 5 year cycles.

Planned Improvements

Area data by land-use category are not estimated for the U.S. territories. A key planned improvement is to incorporate land-use data from these areas into the Inventory. Fortunately, most of the managed land in the United States is included in the current land-use statistics, but a complete accounting is a key goal for the near future. Data sources will also be evaluated for representing land use on federal and non-federal lands in U.S. territories.

Additional work will be conducted to reconcile differences in Forest Land estimates between the NRI and FIA, evaluating the assumption that the majority of discrepancies in Forest Land areas are associated with an over- or under-estimation of Grassland and Wetland area. In some regions of the United States, a discrepancy in Forest Land areas between NRI and FIA may be associated with an over- or under-prediction of other land uses, and an analysis is planned to develop region-specific adjustments.

There are also other databases that may need to be reconciled with the NRI and NLCD datasets, particularly for Settlements and Wetlands. Urban area estimates, used to produce C stock and flux estimates from urban trees, are currently based on population data (1990 and 2000 U.S. Census data). Using the population statistics, “urban clusters” are defined as areas with more than 500 people per square mile. The USFS is currently moving ahead with an urban forest inventory program so that urban forest area estimates will be consistent with FIA forest area estimates outside of urban areas, which would be expected to reduce omissions and overlap of forest area estimates along urban boundary areas.

The implementation criteria will also be expanded in the future, particularly in regard to inclusion of areas managed for mining and petroleum extraction. This criteria will have an impact on the managed land base in Alaska although there will still be large tracts of unmanaged land in this region with virtually no direct influence on GHG emissions from human activity.

7.2 Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks (IPCC Source Category 5A1)

For estimating C stocks or stock change (flux), C in forest ecosystems can be divided into the following five storage pools (IPCC 2003):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 mm diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes the litter, fomic, and humic layers, and all non-living biomass with a diameter less than 7.5 cm at transect intersection, lying on the ground.
- Soil organic C (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the aboveground pools.

In addition, there are two harvested wood pools necessary for estimating C flux:

- Harvested wood products (HWP) in use.
- HWP in solid waste disposal sites (SWDS).

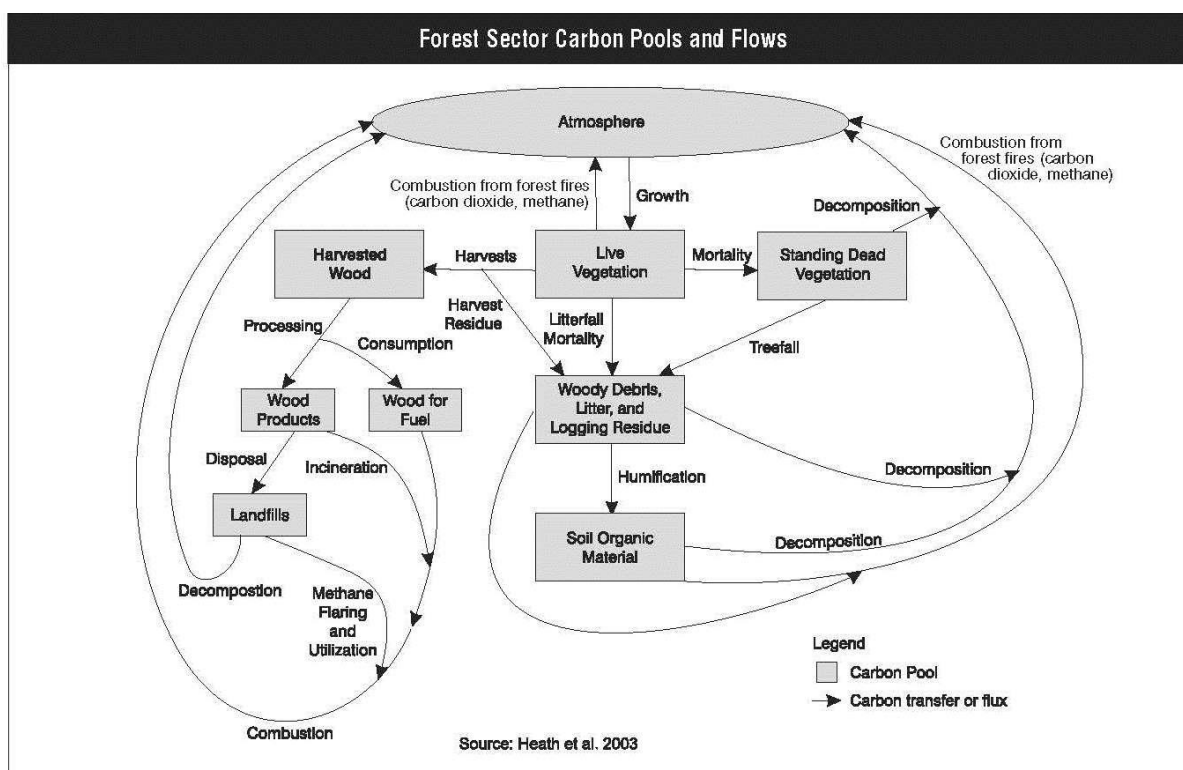
Carbon is continuously cycled among these storage pools and between forest ecosystems and the atmosphere as a result of biological processes in forests (e.g., photosynthesis, respiration, growth, mortality, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, clearing, and replanting). As trees photosynthesize and grow, C is removed from the atmosphere and stored in living tree biomass. As trees die and otherwise deposit litter and debris on the forest floor, C is released to the atmosphere and also is transferred to the soil by organisms that facilitate decomposition.

The net change in forest C is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of C of all vegetation C to the atmosphere. Instead, harvesting transfers a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time as CO₂ when the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases C immediately. Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and C is released to the atmosphere. If wood products are disposed of in SWDS, the C contained in the wood may be released many years or decades later, or may be stored almost permanently in the SWDS.

This section quantifies the net changes in C stocks in the five forest C pools and two harvested wood pools. The net change in stocks for each pool is estimated, and then the changes in stocks are summed over all pools to estimate total net flux. The focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes do not need to be separately itemized in this report. Changes in C stocks from disturbances, such as forest fires, are implicitly included in the net changes. For instance, an inventory conducted after fire counts only the trees that are left. The change between inventories thus accounts for the C changes due to fires; however, it may not be possible to attribute the changes to the disturbance specifically. Similarly, changes in C stocks from natural disturbances, such as wildfires, pest outbreaks, and storms, are implicitly accounted for in the forest inventory approach; however, they are highly variable from year to year. Wildfire events are typically the most severe but other natural disturbance events can result in large C stock losses that are time- and location- specific. The IPCC (2003) recommends reporting C stocks according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. Currently, consistent datasets are just becoming available for the conterminous United States to allow forest land conversions and forest land remaining forest land to be identified, and research is ongoing to properly use that information based on research results. Thus, net changes in all forest-related land, including non-forest land converted to forest and forests converted to non-forest, are reported here.

Forest C storage pools, and the flows between them via emissions, sequestration, and transfers, are shown in Figure 7-2. In the figure, boxes represent forest C storage pools and arrows represent flows between storage pools or between storage pools and the atmosphere. Note that the boxes are not identical to the storage pools identified in this chapter. The storage pools identified in this chapter have been refined in this graphic to better illustrate the processes that result in transfers of C from one pool to another, and emissions to as well as uptake from the atmosphere.

Figure 7-2: Forest Sector Carbon Pools and Flows



Approximately 33 percent (304 million hectares) of the U.S. land area is forested (Smith et al. 2009). The current forest C inventory includes 275 million hectares in the conterminous 48 states (USDA Forest Service 2012a, 2012b) that are considered managed and are included in this inventory. An additional 6 million hectares of southeast and south central Alaskan forest are inventoried and are included here. Some differences exist in forest land defined in Smith et al. (2009) and the forest land included in this report, which is based on USDA Forest Service (2012b). Survey data are not yet available from Hawaii and a large portion of interior Alaska, but estimates of these areas are included in Smith et al. (2009). Alternately, updated survey data for central and western forest land in both Oklahoma and Texas have only recently become available, and these forests contribute to overall C stock reported below. While Hawaii and U.S. territories have relatively small areas of forest land and will thus probably not influence the overall C budget substantially, these regions will be added to the C budget as sufficient data become available. Agroforestry systems are also not currently accounted for in the inventory, since they are not explicitly inventoried by either the FIA program of USDA Forest Service or the NRI of the USDA Natural Resources Conservation Service (Perry et al. 2005).

Sixty-eight percent (208 million hectares) of U.S. forests in Alaska and the conterminous U.S. are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Nine percent of Alaskan forests and 81 percent of forests in the conterminous United States are classified as timberlands. Of the remaining nontimberland forests, 30 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 66 million hectares are lower productivity forest lands (Smith et al. 2009). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than other forest lands.

Forest land area declined by approximately 10 million hectares over the period from the early 1960s to the late 1980s. Since then, forest area has increased by about 12 million hectares (Smith et al. 2009). Current trends in forest area represent an average annual increase of 0.2 percent. In addition to the increase in forest area, the major influences on the current net C flux from forest land are management activities and the ongoing impacts of previous land-use changes. These activities affect the net flux of C by altering the amount of C stored in forest ecosystems. For example, intensified management of forests that leads to an increased rate of growth increases the eventual

biomass density of the forest, thereby increasing the uptake of C.²²⁶ Though harvesting forests removes much of the aboveground C, on average the volume of annual net growth nationwide is about 72 percent higher than the volume of annual removals on timberlands (Smith et al. 2009). The reversion of cropland to forest land increases C storage in biomass, forest floor, and soils. The net effects of forest management and the effects of land-use change involving forest land are captured in the estimates of C stocks and fluxes presented in this chapter.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, and timber harvesting and use have resulted in net uptake (i.e., net sequestration) of C each year from 1990 through 2011. The rate of forest clearing begun in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence C fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally-sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests have also affected net C fluxes. Because most of the timber harvested from U.S. forests is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, significant quantities of C in harvested wood are transferred to long-term storage pools rather than being released rapidly to the atmosphere (Skog and Nicholson 1998, Skog 2008). The size of these long-term C storage pools has increased during the last century.

Changes in C stocks in U.S. forests and harvested wood were estimated to account for net sequestration of 834 Tg CO₂ Eq. (227 Tg C) in 2011 (Table 7-7, Table 7-8, and Table 7-9). In addition to the net accumulation of C in harvested wood pools, sequestration is a reflection of net forest growth and increasing forest area over this period. Overall, average C in forest ecosystem biomass (aboveground and belowground) increased from 54 to 62 Mg C/ha between 1990 and 2012 (see Annex 3-12 for average C densities by specific regions and forest types). Continuous, regular annual surveys are not available over the period for each state; therefore, estimates for non-survey years were derived by interpolation between known data points. Survey years vary from state to state, and national estimates are a composite of individual state surveys. Therefore, changes in sequestration over the interval 1990 to 2011 are the result of the sequences of new inventories for each state. C in forest ecosystem biomass had the greatest effect on total change through increases in C density and total forest land. Management practices that increase C stocks on forest land, as well as afforestation and reforestation efforts, influence the trends of increased C densities in forests and increased forest land in the United States.

Annual net additions to HWP carbon stock were estimated to continue to increase during 2011 from a low in 2009 as inputs to products in use for both solid wood and paper products increased with continued recovery from the recession. Gross inputs to products in use in 2011 were well above the discard rate but net additions to products in use were still about 25 percent below the rate for 2008. The primary reason for overall net additions in recent years is a near stable rate of net additions to products in landfills. Estimates of C additions for 2008, 2009 and 2010 were adjusted downward due to revision in data on softwood pulpwood production, hardwood lumber production, hardwood plywood production, and imports of particleboard and medium density fiberboard. Due to the change in import data, estimates of C storage were reduced more for the Stock Change Accounting approach (Annex Table A-228) than the Production Approach (Table 7-7, Annex Table A-228).

Table 7-7: Net Annual Changes in C Stocks (Tg CO₂/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	2005	2007	2008	2009	2010	2011
Forest	(565.1)	(799.6)	(757.0)	(757.1)	(757.1)	(758.2)	(761.8)
Aboveground							
Biomass	(359.8)	(436.4)	(404.0)	(403.9)	(403.9)	(403.9)	(403.9)
Belowground							
Biomass	(70.3)	(86.0)	(80.1)	(80.1)	(80.1)	(80.1)	(80.1)
Dead Wood	(32.6)	(47.1)	(52.3)	(52.3)	(52.3)	(53.4)	(57.1)

²²⁶ The term “biomass density” refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is 50 percent C by weight.

Litter	(25.0)		(49.6)		(54.5)	(54.5)	(54.5)	(54.5)	(54.5)
Soil Organic Carbon	(77.4)		(180.5)		(166.2)	(166.3)	(166.3)	(166.3)	(166.3)
Harvested Wood	(131.8)		(105.4)		(102.3)	(76.3)	(54.3)	(59.4)	(71.7)
Products in Use	(64.8)		(45.4)		(38.5)	(13.6)	6.8	1.2	(10.0)
SWDS	(67.0)		(59.9)		(63.8)	(62.7)	(61.0)	(60.7)	(61.7)
Total Net Flux	(696.8)		(905.0)		(859.3)	(833.3)	(811.3)	(817.6)	(833.5)

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a portion of managed forests in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Forest area estimates are based on interpolation and extrapolation of inventory data as described in the text and in Annex 3.12. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Table 7-8: Net Annual Changes in C Stocks (Tg C/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990		2005		2007	2008	2009	2010	2011
Forest	(154.1)		(218.1)		(206.5)	(206.5)	(206.5)	(206.8)	(207.8)
Aboveground Biomass	(98.1)		(119.0)		(110.2)	(110.2)	(110.2)	(110.2)	(110.2)
Belowground Biomass	(19.2)		(23.4)		(21.8)	(21.8)	(21.8)	(21.8)	(21.8)
Dead Wood	(8.9)		(12.9)		(14.3)	(14.3)	(14.3)	(14.6)	(15.6)
Litter	(6.8)		(13.5)		(14.9)	(14.9)	(14.9)	(14.9)	(14.9)
Soil Organic C	(21.1)		(49.2)		(45.3)	(45.4)	(45.4)	(45.4)	(45.4)
Harvested Wood	(35.9)		(28.7)		(28.1)	(20.8)	(14.8)	(16.2)	(19.5)
Products in Use	(17.7)		(12.4)		(10.5)	(3.7)	1.8	0.3	(2.7)
SWDS	(18.3)		(16.3)		(17.4)	(17.1)	(16.6)	(16.5)	(16.8)
Total Net Flux	(190.0)		(246.8)		(234.4)	(227.3)	(221.3)	(223.0)	(227.3)

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a portion of managed lands in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Stock estimates for forest and harvested wood C storage pools are presented in Table 7-9. Together, the aboveground live and forest soil pools account for a large proportion of total forest C stocks. C stocks summed for non-soil pools increased over time Figure 7-3. Therefore, C sequestration was greater than C emissions from forests, as discussed above. Figure 7-4 shows county-average C densities for live trees on forest land, including both above- and belowground biomass.

Table 7-9: Forest area (1000 ha) and C Stocks (Tg C) in Forest and Harvested Wood Pools

	1990		2005		2007	2008	2009	2010	2011
Forest Area (1000 ha)	271,794		279,781		281,090	281,694	282,300	282,905	283,510
Carbon Pools (Tg C)									
Forest	38,777		41,192		41,618	41,825	42,031	42,238	42,444
Aboveground Biomass	12,284		13,912		14,146	14,256	14,366	14,476	14,586
Belowground Biomass	2,432		2,752		2,798	2,820	2,842	2,863	2,885
Dead Wood	2,161		2,342		2,368	2,383	2,397	2,411	2,426
Litter	4,816		4,880		4,908	4,923	4,937	4,952	4,967
Soil Organic C	17,084		17,306		17,399	17,444	17,489	17,535	17,580
Harvested Wood	1,859		2,325		2,383	2,411	2,432	2,447	2,463

Products in Use	1,231		1,436		1,460	1,471	1,474	1,472	1,472
SWDS	628		890		923	941	958	974	991
Total C Stock	40,637		43,517		44,002	44,236	44,463	44,684	44,907

Note: Forest area estimates include portions of managed forests in Alaska for which survey data are available.

Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a large portion of Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Forest area estimates are based on interpolation and extrapolation of inventory data as described in Smith et al. (2010) and in Annex 3.12. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Inventories are assumed to represent stocks as of January 1 of the inventory year. Flux is the net annual change in stock. Thus, an estimate of flux for 2006 requires estimates of C stocks for 2006 and 2007.

Figure 7-3: Estimates of Net Annual Changes in C Stocks for Major C Pools

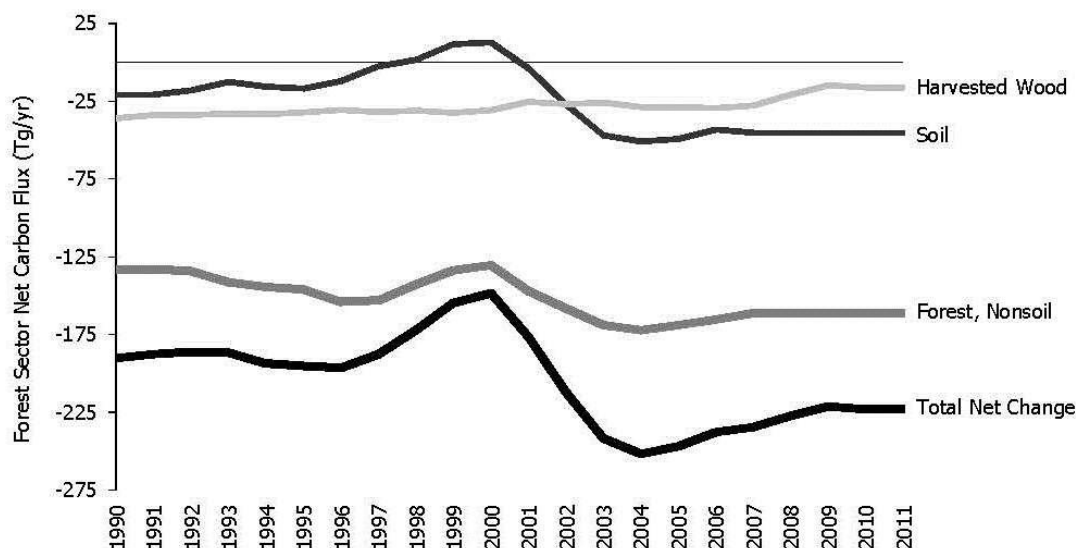
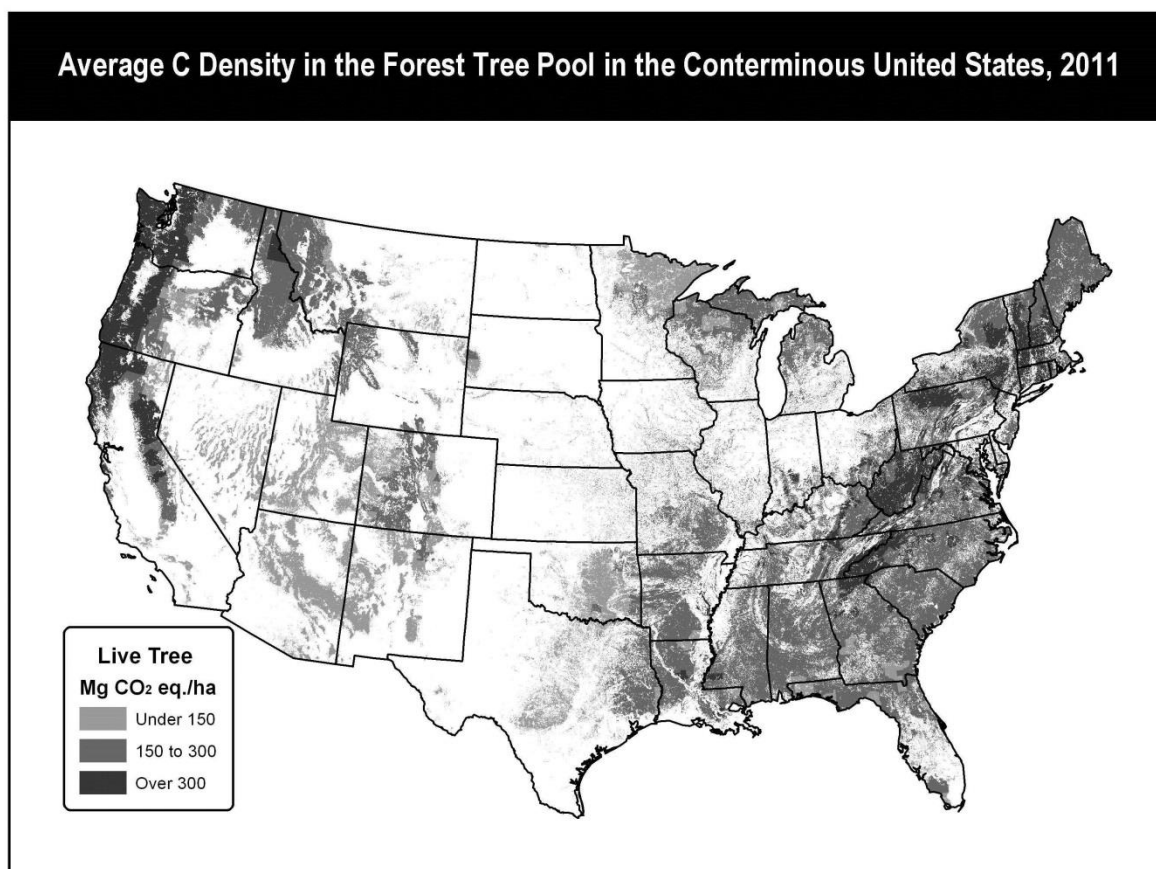


Figure 7-4: Average C Density in the Forest Tree Pool in the Conterminous United States, 2010



Box 7-2: CO₂ Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly accounts for emissions due to disturbances such as forest fires, because only C remaining in the forest is estimated. Net C stock change is estimated by subtracting consecutive C stock estimates. A forest fire disturbance removes C from the forest. The inventory data on which net C stock estimates are based already reflect this C loss. Therefore, estimates of net annual changes in C stocks for U.S. forestland already account for CO₂ emissions from forest fires occurring in the lower 48 states as well as in the proportion of Alaska's managed forest land captured in this Inventory. Because it is of interest to quantify the magnitude of CO₂ emissions from fire disturbance, these estimates are highlighted here, using the full extent of available data. Non-CO₂ greenhouse gas emissions from forest fires are also quantified in a separate section below.

The IPCC (2003) methodology and IPCC (2006) default combustion factor for wildfire were employed to estimate CO₂ emissions from forest fires. CO₂ emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska in 2011 were estimated to be 225.3 Tg CO₂/yr. This amount is masked in the estimate of net annual forest C stock change for 2011 because this net estimate accounts for the amount sequestered minus any emissions.

Table 7-10: Estimates of CO₂ (Tg/yr) Emissions for the Lower 48 States and Alaska^a

Year	CO ₂ emitted from Wildfires in Lower 48 States (Tg/yr)	CO ₂ emitted from Prescribed Fires in Lower 48 States (Tg/yr)	CO ₂ emitted from Wildfires in Alaska (Tg/yr)	Total CO ₂ emitted (Tg/yr)
1990	32.4	7.1	+	39.5
2005	107.0	20.7	+	127.7
2007	203.5	24.8	+	228.3
2008	122.5	15.3	+	137.8
2009	70.6	20.1	+	90.6
2010	54.9	19.3	+	74.2
2011	208.0	17.3	+	225.3

+ Does not exceed 0.05 Tg CO₂ Eq.

^a Note that these emissions have already been accounted for in the estimates of net annual changes in C stocks, which account for the amount sequestered minus any emissions.

Methodology and Data Sources

The methodology described herein is consistent with IPCC (2003, 2006) and IPCC/UNEP/OECD/IEA (1997). Forest ecosystem C stocks and net annual C stock change were determined according to stock-difference methods, which involved applying C estimation factors to forest inventory data and interpolating between successive inventory-based estimates of C stocks. Harvested wood C estimates were based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of the amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the C in forest ecosystems or harvested wood products is provided here. See Annex 3.12 for details and additional information related to the methods and data.

Forest Ecosystem Carbon from Forest Inventory

Forest ecosystem stock and flux estimates are based on the stock-difference method and calculations for all estimates are in units of C. Separate estimates were made for the five IPCC C storage pools described above. All estimates were based on data collected from the extensive array of permanent forest inventory plots in the United States as well as models employed to fill gaps in field data (USDA Forest Service 2012b, 2012c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. A combination of tiers as outlined by IPCC (2006) was used. The Tier 3 biomass C values were calculated from forest inventory tree-level data. The Tier 2 dead organic and soil C pools were based on empirical or process models from the inventory data. All C conversion factors are specific to regions or individual states within the United States, which were further classified according to characteristic forest types within each region.

The first step in developing forest ecosystem estimates is to identify useful inventory data and resolve any inconsistencies among datasets. Forest inventory data were obtained from the FIA program (Frayer and Furnival 1999, USDA Forest Service 2012b). Inventories include data collected on permanent inventory plots on forest lands and were organized as a number of separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time.²²⁷ Many of the more recent annual inventories reported for states were

²²⁷ Forest land in the United States includes land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood.

represented as “moving window” averages, which means that a portion—but not all—of the previous year’s inventory is updated each year (USDA Forest Service 2012d). Forest C calculations were organized according to these state surveys, and the frequency of surveys varies by state. All available data sets were identified for each state starting with pre-1990 data, and all unique surveys were identified for stock and change calculations. Since C stock change is based on differences between successive surveys within each state, accurate estimates of net C flux thus depend on consistent representation of forest land between these successive inventories. In order to achieve this consistency from 1990 to the present, states were sometimes subdivided into sub-state areas where the sum of sub-state inventories produces the best whole-state representation of C change as discussed in Smith et al. (2010).

The principal FIA datasets employed are freely available for download at USDA Forest Service (2012b) as the Forest Inventory and Analysis Database (FIADB) Version 5.1 (USDA Forest Service 2012, Woudenberg et al. 2010). However, to achieve consistent representation (spatial and temporal), three other general sources of past FIA data were included as necessary. First, older FIA plot- and tree-level data—not in the current FIADB format—were used if available. Second, Resources Planning Act Assessment (RPA) databases, which are periodic, plot-level only, summaries of state inventories, were used to provide the data at or before 1990. Finally, an additional forest inventory data source used was the Integrated Database (IDB), which is a compilation of periodic forest inventory data from the 1990s for California, Oregon, and Washington (Waddell and Hiserote 2005). These IDB data were identified by Heath et al. (2011) as the most appropriate non-FIADB sources for these states and were included in this inventory. See USDA Forest Service (2012a) for information on current and older data as well as additional FIA Program features. A detailed list of the specific forest inventory data used in this inventory is in Annex 3.12.

Forest C stocks were estimated from inventory data by a collection of conversion factors and models (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003, Smith et al. 2004, Smith et al. 2006), which have been formalized in an FIADB-to-C calculator (Smith et al. 2010). The conversion factors and model coefficients were categorized by region and forest type, and forest C stock estimates were calculated from application of these factors at the scale of FIA inventory plots. The results were estimates of C density (Mg C per hectare) for six forest ecosystem pools: live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and soil organic matter. The six C pools used in the FIADB-to-C calculator were aggregated to the 5 C pools defined by IPCC (2006): aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter. The live-tree and understory C were pooled as biomass, and standing dead trees and down dead wood were pooled as dead wood, in accordance with IPCC (2006).

Once plot-level C stocks were calculated as C densities on *Forest Land Remaining Forest Land* for the five IPCC (2006) reporting pools, the stocks were expanded to population estimates according to methods appropriate to the respective inventory data (for example, see Bechtold and Patterson (2005)). These expanded C stock estimates were summed to state or sub-state total C stocks. Annualized estimates of C stocks were developed by using available FIA inventory data and interpolating or extrapolating to assign a C stock to each year in the 1990 through 2012 time series. Flux, or net annual stock change, was estimated by calculating the difference in stocks between two successive years and applying the appropriate sign convention; net increases in ecosystem C were identified as negative flux. By convention, inventories were assigned to represent stocks as of January 1 of the inventory year; an estimate of flux for 1996 required estimates of C stocks for 1996 and 1997, for example. Additional discussion of the use of FIA inventory data and the C conversion process is in Annex 3.12.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at diameter breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above- and below-ground biomass components. If inventory plots included data on individual trees, tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method. Some of the older forest inventory data in use for these estimates did not provide measurements of individual trees. Examples of these data include plots with incomplete or missing tree data or the RPA plot-level summaries. The C estimates for these plots were based on average densities (metric tons C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applies to 5 percent of the forest land inventory-plot-to-C conversions within the 183 state-level surveys utilized here.

Understory vegetation is a minor component of biomass, which is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. In the current inventory, it was assumed that 10 percent of total understory C mass is belowground. Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory frequently represented over 1 percent of C in biomass, but its contribution rarely exceeded 2 percent of the total.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, down dead wood, and litter—with C stocks estimated from sample data or modeled. The standing dead tree C pools include aboveground and belowground (coarse root) mass and include trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011, Harmon et al. 2011). Similar to the situation with live tree data, some of the older forest inventory data did not provide sufficient data on standing dead trees to make accurate population-level estimates. The C estimates for these plots were based on average densities (metric tons C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applied to 25 percent of the forest land inventory-plot-to-C conversions within the 183 state-level surveys utilized here. Down dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al., Woodall and Monleon 2008, Woodall et al. In Review). Down dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from state to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Estimates are based on equations of Smith and Heath (2002).

Carbon in Forest Soil

Soil organic C includes all organic material in soil to a depth of 1 meter but excludes the coarse roots of the biomass or dead wood pools. Estimates of SOC were based on the national STATSGO spatial database (USDA 1991), which includes region and soil type information. SOC determination was based on the general approach described by Amichev and Galbraith (2004). Links to FIA inventory data were developed with the assistance of the USDA Forest Service FIA Geospatial Service Center by overlaying FIA forest inventory plots on the soil C map. This method produced mean SOC densities stratified by region and forest type group. It did not provide separate estimates for mineral or organic soils but instead weighted their contribution to the overall average based on the relative amount of each within forest land. Thus, forest SOC is a function of species and location, and net change also depends on these two factors as total forest area changes. In this respect, SOC provides a country-specific reference stock for 1990-present, but it does not reflect effects of past land use.

Harvested Wood Carbon

Estimates of the HWP contribution to forest C sinks and emissions (hereafter called “HWP Contribution”) were based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating HWP C. IPCC (2006) provides methods that allow Parties to report HWP Contribution using one of several different accounting approaches: production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP C stocks (see Annex 3.12 for more details about each approach). The United States used the production accounting approach to report HWP Contribution. Under the production approach, C in exported wood was estimated as if it remains in the United States, and C in imported wood was not included in inventory estimates. Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.12). Annual estimates of change were calculated by tracking the additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in solid waste disposal sites (SWDS).

Solidwood products added to pools include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end-uses. There is one product category and one end-use category for paper. Additions to and removals from pools were tracked beginning in 1900, with the exception that additions of softwood lumber to housing began in 1800. Solidwood and paper product production

and trade data were taken from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census; 1976; Ulrich, 1985, 1989; Steer 1948; AF&PA 2006a 2006b; Howard 2003, 2007). Estimates for disposal of products reflected the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that were in sanitary landfills versus dumps.

There are five annual HWP variables that were used in varying combinations to estimate HWP Contribution using any one of the three main approaches listed above. These are:

- (1A) annual change of C in wood and paper products in use in the United States,
- (1B) annual change of C in wood and paper products in SWDS in the United States,
- (2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,
- (2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,
- (3) C in imports of wood, pulp, and paper to the United States,
- (4) C in exports of wood, pulp and paper from the United States, and
- (5) C in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yielded the estimate for HWP Contribution under the production accounting approach. A key assumption for estimating these variables was that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty and Time Series Consistency

A quantitative uncertainty analysis placed bounds on current flux for forest ecosystems as well as C in harvested wood products through Monte Carlo Stochastic Simulation of the Methods described above and probabilistic sampling of C conversion factors and inventory data. See Annex 3.12 for additional information. The 2011 net annual change for forest C stocks was estimated to be between -957 and -712 Tg CO₂ Eq. at a 95 percent confidence level. This includes a range of -883.7 to -641.1 Tg CO₂ Eq. in forest ecosystems and -90.9 to -54.8 Tg CO₂ Eq. for HWP.

Table 7-11: Tier 2 Quantitative Uncertainty Estimates for Net CO₂ Flux from Forest Land Remaining Forest Land: Changes in Forest C Stocks (Tg CO₂ Eq. and Percent)

Source	Gas	2011 Flux Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Flux Estimate ^a			
			(Tg CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem	CO ₂	(761.8)	(883.7)	(641.1)	-16.0	+15.8
Harvested Wood						
Products	CO ₂	(71.7)	(90.9)	(54.8)	-26.8	+23.6
Total Forest	CO₂	(833.5)	(956.5)	(712.1)	-14.8	+14.6

Note: Parentheses indicate negative values or net sequestration.

^a Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2011. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

As discussed above, the FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous United States, dating back to 1952. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for C stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (USDA Forest Service 2012d).

Many key calculations for estimating current forest C stocks based on FIA data were developed to fill data gaps in assessing forest C and have been in use for many years to produce national assessments of forest C stocks and stock changes (see additional discussion and citations in the Methodology section above and in Annex 3.12). General quality control procedures were used in performing calculations to estimate C stocks based on survey data. For example, the derived C datasets, which include inventory variables such as areas and volumes, were compared to standard inventory summaries such as the forest resource statistics of Smith et al. (2009) or selected population estimates generated from FIADB 5.1, which are available at an FIA internet site (USDA Forest Service 2012b). Agreement between the C datasets and the original inventories is important to verify accuracy of the data used. Finally, C stock estimates were compared with previous inventory report estimates to ensure that any differences could be explained by either new data or revised calculation methods (see the “Recalculations” discussion, below).

Estimates of the HWP variables and the HWP contribution under the production accounting approach use data from U.S. Census and USDA Forest Service surveys of production and trade. Factors to convert wood and paper to units C are based on estimates by industry and Forest Service published sources. The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual C change in solid wood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needs to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half-life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in C in products in use in the United States and, to a lesser degree, reduce uncertainty in estimates of annual change in C in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by ensuring that estimates of CH₄ emissions from landfills based on EPA (2006) data are reasonable in comparison with CH₄ estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

In addition to annual updates to most-recent inventories for many states, four additional changes in method or data reduction for the current Inventory affected the national stock and change estimates for forest ecosystems. Of these, the modification of the down dead wood estimates to incorporate plot level sampling of down woody material (Woodall et al. 2010, Woodall et al. In Review) resulted in the greatest impact on total forest C stocks. Nationally, estimates for C in down dead wood stocks decreased by about 8 percent. A second change was a modification in the approach to determining the necessary volumes as inputs to the tree biomass equations, which only affected a few of the periodic (i.e., older) inventories. Next, we identified that the older forest inventories classified as woodlands on National Forests in Colorado included a spatial extent substantially lower than current inventories of that classification. The older inventories were dropped from our calculations because of the inconsistency (see annex 3.12 for specifics of inventories in use). Finally, the current FIADB 5.1 data do not include the periodic survey for Alaska as was included in the previous Inventory (EPA 2012). Therefore we retained the estimates based on FIADB 4.0 after making appropriate adjustments consistent with this year’s Inventory (e.g., the modified down dead wood estimates). This represents a change in method—that is, including older FIADB data—that does not affect the estimates, because it maintains consistency between successive Inventories.

Estimates for C additions to harvested wood products pools were adjusted due to revision to data for softwood pulpwood production (2006 to 2010), hardwood lumber production (2007 to 2010), hardwood plywood production (2008 to 2010), and imports of particleboard and medium density fiberboard (1998 to 2010). Revisions are

contained in Howard (forthcoming). Estimates of the total C stock have been adjusted to represent the stock at the beginning of the year rather than the end of the year to match the beginning year estimates for forest stocks. Previously the estimates had been for the end of the year. This reduced the total stock level estimate for years through 2010 by 20 to 30 Tg C.

Planned Improvements

The ongoing annual surveys by the FIA Program will improve the precision of forest C estimates as new state surveys become available (USDA Forest Service 2012b), particularly in western states. The annual surveys will eventually include all states. To date, three states are not yet reporting any data from the annualized sampling design of FIA: Hawaii, New Mexico and Wyoming. Estimates for these states are currently based on older, periodic data. Hawaii and U.S. territories will also be included when appropriate forest C data are available. In addition, the more intensive sampling of fine woody debris, litter, and SOC on some of the permanent FIA plots continues and will substantially improve resolution of C pools at the plot level for all U.S. forest land as this information becomes available (Woodall et al. 2011b). Improved resolution, incorporating more of Alaska's forests, and using annualized sampling data as it becomes available for those states currently not reporting are planned for future reporting.

As more information becomes available about historical land use, the ongoing effects of changes in land use and forest management will be better accounted for in estimates of soil C (Birdsey and Lewis 2003, Woodbury et al. 2006, Woodbury et al. 2007). Currently, soil C estimates are based on the assumption that soil C density depends only on broad forest type group, not on land-use history, but long-term residual effects on soil and forest floor C stocks are likely after land-use change. Estimates of such effects depend on identifying past land use changes associated with forest lands.

Similarly, agroforestry practices, such as windbreaks or riparian forest buffers along waterways, are not currently accounted for in the inventory. In order to properly account for the C stocks and fluxes associated with agroforestry, research will be needed that provides the basis and tools for including these plantings in a nation-wide inventory, as well as the means for entity-level reporting.

Non-CO₂ Emissions from Forest Fires

Emissions of non-CO₂ gases from forest fires were estimated using the default IPCC (2003) methodology incorporating default IPCC (2006) emissions factors and combustion factor for wildfires. Emissions from this source in 2011 were estimated to be 14.2 Tg CO₂ Eq. of CH₄ and 11.6 Tg CO₂ Eq. of N₂O, as shown in Table 7-12 and Table 7-13. The estimates of non-CO₂ emissions from forest fires account for wildfires in the lower 48 states and Alaska as well as prescribed fires in the lower 48 states.

Table 7-12: Estimated Non-CO₂ Emissions from Forest Fires (Tg CO₂ Eq.) for U.S. Forests^a

Gas	1990	2005	2007	2008	2009	2010	2011
CH ₄	2.5	8.0	14.4	8.7	5.7	4.7	14.2
N ₂ O	2.0	6.6	11.7	7.1	4.7	3.8	11.6
Total	4.5	14.6	26.1	15.7	10.4	8.5	25.7

^a Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003, 2006).

Table 7-13: Estimated Non-CO₂ Emissions from Forest Fires (Gg Gas) for U.S. Forests^a

Gas	1990	2005	2007	2008	2009	2010	2011
CH ₄	118	383	684	413	271	222	675
N ₂ O	7	21	38	23	15	12	37

^a Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003, 2006).

Methodology

The IPCC (2003) Tier 2 default methodology was used to calculate non-CO₂ emissions from forest fires. However, more up-to-date default emission factors from IPCC (2006) were converted into gas-specific emission ratios and incorporated into the methodology. Estimates of CH₄ and N₂O emissions were calculated by multiplying the total estimated CO₂ emitted from forest burned by the gas-specific emissions ratios. CO₂ emissions were estimated by multiplying total C emitted (Table 7-14) by the C to CO₂ conversion factor of 44/12 and by 92.8 percent, which is the estimated proportion of C emitted as CO₂ (Smith 2008a). The equations used were:

$$\text{CH}_4 \text{ Emissions} = (\text{C released}) \times 92.8\% \times (44/12) \times (\text{CH}_4 \text{ to CO}_2 \text{ emission ratio})$$

$$\text{N}_2\text{O Emissions} = (\text{C released}) \times 92.8\% \times (44/12) \times (\text{N}_2\text{O to CO}_2 \text{ emission ratio})$$

Estimates for C emitted from forest fires are the same estimates used to generate estimates of CO₂ presented earlier in Box 7-1. Estimates for C emitted include emissions from wildfires in both Alaska and the lower 48 states as well as emissions from prescribed fires in the lower 48 states only (based on expert judgment that prescribed fires only occur in the lower 48 states) (Smith 2008a). The IPCC (2006) default combustion factor of 0.45 for “all ‘other’ temperate forests” was applied in estimating C emitted from both wildfires and prescribed fires. See the explanation in Annex 3.12 for more details on the methodology used to estimate C emitted from forest fires.

Table 7-14: Estimated Carbon Released from Forest Fires for U.S. Forests

Year	C Emitted (Tg/yr)
1990	11.6
2005	37.5
2007	67.1
2008	40.5
2009	26.6
2010	21.8
2011	66.2

Uncertainty and Time-Series Consistency

Non-CO₂ gases emitted from forest fires depend on several variables, including: forest area for Alaska and the lower 48 states; average C densities for wildfires in Alaska, wildfires in the lower 48 states, and prescribed fires in the lower 48 states; emission ratios; and combustion factor values (proportion of biomass consumed by fire). To quantify the uncertainties for emissions from forest fires, a Monte Carlo (Tier 2) uncertainty analysis was performed using information about the uncertainty surrounding each of these variables. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-15.

Table 7-15: Tier 2 Quantitative Uncertainty Estimates of Non-CO₂ Emissions from Forest Fires in Forest Land Remaining Forest Land (Tg CO₂ Eq. and Percent)

Source	Gas	2011 Emission Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO ₂ Eq.) (%)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO ₂ Emissions from Forest Fires	CH ₄	14.2	2.6	37.6	-82%	+165%
Non-CO ₂ Emissions from Forest Fires	N ₂ O	11.6	2.2	31.0	-81%	+169%

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2011. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

For the current Inventory, non-CO₂ emissions were calculated using the 2006 IPCC default emission factors for CH₄ and N₂O instead of the 2003 IPCC default emission factors. These default emission factors were converted to CH₄ to CO₂ and N₂O to CO₂ emission ratios and then multiplied by CO₂ emissions to estimate CH₄ and N₂O emissions. The previous 2003 IPCC methodology provides emission ratios that are multiplied by total C emitted.

The National Association of State Foresters (NASF) releases data on land under wildland protection every several years. In 2011, NASF released these data for the year 2008, which affected the ratio of forest land to land under wildland protection for the years 2007 through 2009. For each of these three years, the updated ratio decreased the forest area burned estimates for the lower forty-eight states by around 15 percent. See the explanation in Annex 3.12 for more details on how the forestland to land under wildland protection ratio is used to calculate forest fire emissions.

In previous Inventory reports, the methodology has assumed that the C density of forest areas burned in wild and prescribed fires does not vary between years. This assumption has been in contrast to the forest C stock estimates, which are updated annually for all years based on data from the USDA Forest Service. The methodology adopted for the current and previous Inventory improves the C density factors by incorporating dynamic C density values based on the annual C pool data provided by the USDA Forest Service for the years 1990 to 2011. As a result of this update, estimates of CO₂ and non-CO₂ emissions from wild and prescribed fires decreased by between 1 and 4 percent as compared to the estimates included in the previous Inventory. This decrease occurred because the dynamic C density values calculated were on average 1% lower (depending on the year) than the C density values previously used for the methodology. For more information on how C density contributes to estimates of emissions from forest fires, see Annex 3.12.

Planned Improvements

The default combustion factor of 0.45 from IPCC (2006) was applied in estimating C emitted from both wildfires and prescribed fires. Additional research into the availability of a combustion factor specific to prescribed fires is being conducted.

Direct N₂O Fluxes from Forest Soils (IPCC Source Category 5A1)

Of the synthetic nitrogen (N) fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropped soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once approximately 20 years later). Thus, while the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, the average annual application is quite low as inferred by dividing all forest land that may undergo N fertilization at some point during its growing cycle by the amount of N fertilizer added to these forests in a given year. Direct N₂O emissions from forest soils in 2011 were 0.4 Tg CO₂ Eq. (1 Gg). Emissions have increased by 455 percent from 1990 to 2011 as a result of an increase in the area of N fertilized pine plantations in the southeastern United States and Douglas-fir timberland in western Washington and Oregon. Total forest soil N₂O emissions are summarized in Table 7-16.

Table 7-16: Direct N₂O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO₂ Eq. and Gg N₂O)

Year	Tg CO ₂ Eq.	Gg
1990	0.1	0.2
2005	0.4	1.2
2007	0.4	1.2
2008	0.4	1.2
2009	0.4	1.2
2010	0.4	1.2
2011	0.4	1.2

Note: These estimates include direct N₂O emissions from N fertilizer additions only. Indirect N₂O emissions from fertilizer additions are reported in the Agriculture chapter. These estimates include emissions from both *Forest Land Remaining Forest Land* and from *Land Converted to Forest Land*.

Methodology

The IPCC Tier 1 approach was used to estimate N₂O from soils within *Forest Land Remaining Forest Land*. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted were for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also accounted for N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N₂O emissions from fertilizer applications to forests were based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al. 2007; Fox et al. 2007). Not accounting for fertilizer applied to non-pine plantations is justified because fertilization is routine for pine forests but rare for hardwoods (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer was multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast were not available for 2005, 2006, 2007 and 2008, so data from 2004 were used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir was accounted for, because the vast majority (~95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir (Briggs 2007). Estimates of total Douglas-fir area and the portion of fertilized area were multiplied to obtain annual area estimates of fertilized Douglas-fir stands. The annual area estimates were multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate total N applied (Briggs 2007), and the total N applied to forests was multiplied by the IPCC (2006) default emission factor of 1 percent to estimate direct N₂O emissions. The volatilization and leaching/runoff N fractions for forest land, calculated according to the IPCC default factors of 10 percent and 30 percent, respectively, were included with the indirect emissions in the Agricultural Soil Management source category (consistent with reporting guidance that all indirect emissions are included in the Agricultural Soil Management source category).

Uncertainty and Time-Series Consistency

The amount of N₂O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N₂O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default methodology, except variation in estimated fertilizer application rates and estimated areas of forested land receiving N fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only synthetic N fertilizers are captured, so applications of organic N fertilizers are not estimated. However, the total quantity of

organic N inputs to soils is included in the Agricultural Soil Management and *Settlements Remaining Settlements* sections.

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates were assigned a default level²²⁸ of uncertainty at ± 50 percent, and area receiving fertilizer was assigned a ± 20 percent according to expert knowledge (Binkley 2004). IPCC (2006) provided estimates for the uncertainty associated with direct N₂O emission factor for synthetic N fertilizer application to soils. Quantitative uncertainty of this source category was estimated through the IPCC-recommended Tier 2 uncertainty estimation methodology. The uncertainty ranges around the 2005 activity data and emission factor input variables were directly applied to the 2011 emissions estimates. The results of the quantitative uncertainty analysis are summarized in Table 7-17. N₂O fluxes from soils were estimated to be between 0.1 and 1.1 Tg CO₂ Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the 2011 emission estimate of 0.4 Tg CO₂ Eq.

Table 7-17: Quantitative Uncertainty Estimates of N₂O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO₂ Eq. and Percent)

Source	Gas	2011 Emission Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate			
			(Tg CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Land Remaining Forest Land: N ₂ O Fluxes from Soils	N ₂ O	0.4	0.1	1.1	-59%	+211%

Note: This estimate includes direct N₂O emissions from N fertilizer additions to both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Planned Improvements

State-level area data will be obtained for southeastern pine plantations and northwestern Douglas-fir forests to estimate soil N₂O emission by state and provide information about regional variation in emission patterns.

7.3 Land Converted to Forest Land (IPCC Source Category 5A2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to forest each year, just as forest land is converted to other uses. However, the magnitude of these changes is not currently known. Given the paucity of available land-use information relevant to this particular IPCC source category, it is not possible to separate CO₂ or N₂O fluxes on *Land Converted to Forest Land* from fluxes on *Forest Land Remaining Forest Land* at this time.

²²⁸ Uncertainty is unknown for the fertilization rates so a conservative value of $\pm 50\%$ was used in the analysis.

7.4 Cropland Remaining Cropland (IPCC Source Category 5B1)

Mineral and Organic Soil Carbon Stock Changes

Soils contain both organic and inorganic forms of C, but SOC stocks are the main source and sink for atmospheric CO₂ in most soils. Changes in inorganic C stocks are typically minor. In addition, SOC is the dominant organic C pool in cropland ecosystems, because biomass and dead organic matter have considerably less C and those pools are relatively ephemeral. IPCC (2006) recommends reporting changes in SOC stocks due to agricultural land-use and management activities on mineral and organic soils.²²⁹

Typical well-drained mineral soils contain from 1 to 6 percent organic C by weight, although mineral soils that are saturated with water for substantial periods during the year may contain significantly more C (NRCS 1999). Conversion of mineral soils from their native state to agricultural uses can cause as much as half of the SOC to be decomposed and the C lost to the atmosphere. The rate and ultimate magnitude of C loss will depend on pre-conversion conditions, conversion method and subsequent management practices, climate, and soil type. In the tropics, 40 to 60 percent of the C loss generally occurs within the first 10 years following conversion; C stocks continue to decline in subsequent decades but at a much slower rate. In temperate regions, C loss can continue for several decades, reducing stocks by 20 to 40 percent of native C levels. Eventually, the soil can reach a new equilibrium that reflects a balance between C inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and C loss through microbial decomposition of organic matter. However, land use, management, and other conditions may change before the new equilibrium is reached. The quantity and quality of organic matter inputs and their rate of decomposition are determined by the combined interaction of climate, soil properties, and land use. Land use and agricultural practices such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, and flooding can modify both organic matter inputs and decomposition, and thereby result in a net flux of C to or from the pool of soil C.

Organic soils, also referred to as histosols, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999, Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), forming under inundated conditions in which minimal decomposition of plant residue occurs. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil, which accelerates the rate of decomposition and CO₂ emissions. Because of the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time. The rate of CO₂ emissions varies depending on climate and composition (i.e., decomposability) of the organic matter. Also, the use of organic soils for annual crop production leads to higher C loss rates than drainage of organic soils in grassland or forests, due to deeper drainage and more intensive management practices in cropland (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997). Carbon losses are estimated from drained organic soils under both grassland and cropland management in this Inventory.

Cropland Remaining Cropland includes all cropland in an inventory year that had been cropland for the last 20 years according to the USDA NRI land-use survey (USDA-NRCS 2009).²³⁰ The inventory includes all privately-owned croplands in the conterminous United States and Hawaii, but there is a minor amount of cropland on federal lands that is not currently included in the estimation of C stock changes, leading to a discrepancy between the total amount of managed area in *Cropland Remaining Cropland* (see Section 7.1) and the cropland area included in the Inventory. It is important to note that plans are being made to include federal croplands in future C inventories.

²²⁹ CO₂ emissions associated with liming are also estimated but are included in a separate section of the report.

²³⁰ NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications were based on less than 20 years from 1990 to 2001.

The area of *Cropland Remaining Cropland* changes through time as land is converted to or from cropland management. CO₂ emissions and removals²³¹ due to changes in mineral soil C stocks are estimated using a Tier 3 approach for the majority of annual crops. A Tier 2 IPCC method is used for the remaining crops (vegetables, tobacco, perennial/horticultural crops, and rice) not included in the Tier 3 method. In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale) and for additional changes in mineral soil C stocks that were not addressed with the Tier 3 approach (i.e., change in C stocks after 2003 due to Conservation Reserve Program enrollment). Emissions from organic soils are estimated using a Tier 2 IPCC method.

Of the two sub-source categories, land-use and land management of mineral soils was the most important component of total net C stock change in the early part of the time series, but emissions from organic soils nearly exceeded mineral soils in the latter part of the time series (see Table 7-18 and Table 7-19). In 2011, mineral soils were estimated to remove 29.7 Tg CO₂ Eq. (8.1 Tg C). This rate of C storage in mineral soils represented about a 51 percent decrease in the rate since the initial reporting year of 1990. Emissions from organic soils were 26.8 Tg CO₂ Eq. (7.3 Tg C) in 2011, which was similar to the emissions in 1990. In total, U.S. agricultural soils in *Cropland Remaining Cropland* sequestered approximately 2.9 Tg CO₂ Eq. (0.8 Tg C) in 2011.

Table 7-18: Net CO₂ Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg CO₂ Eq.)

Soil Type	1990	2005	2007	2008	2009	2010	2011
Mineral Soils	(60.4)	(47.1)	(33.4)	(32.0)	(31.4)	(29.8)	(29.7)
Organic Soils	26.3	26.8	26.8	26.8	26.8	26.8	26.8
Total Net Flux	(34.1)	(20.3)	(6.6)	(5.2)	(4.6)	(3.0)	(2.9)

Table 7-19: Net CO₂ Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg C)

Soil Type	1990	2005	2007	2008	2009	2010	2011
Mineral Soils	(16.5)	(12.9)	(9.1)	(8.7)	(8.6)	(8.1)	(8.1)
Organic Soils	7.2	7.3	7.3	7.3	7.3	7.3	7.3
Total Net Flux	(9.3)	(5.5)	(1.8)	(1.4)	(1.2)	(0.8)	(0.8)

The net reduction in soil C accumulation over the time series (51 percent lower for 2011, relative to 1990) was largely due to the declining influence of annual cropland enrolled in the Conservation Reserve Program, which began in the late 1980s. However, there were still positive increases in C stocks from land enrolled in the reserve program, as well as intensification of crop production by limiting the use of bare-summer fallow in semi-arid regions, increased hay production, and adoption of conservation tillage (i.e., reduced- and no-till practices).

The spatial variability in 2011 annual CO₂ flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-5 and Figure 7-6. The highest rates of net C accumulation in mineral soils occurred in the Midwest, which is the area with the largest amounts of cropland managed with conservation tillage, and the south-central and northwest regions. Emissions from organic soils were highest in Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California), coinciding with largest concentrations of organic soils in the United States that are used for agricultural production.

²³¹ Note that removals occur through crop and forage uptake of CO₂ into biomass C that is later incorporated into soil pools.

Figure 7-5: Total Net Annual CO₂ Flux for Mineral Soils under Agricultural Management within States, 2011, Cropland Remaining Cropland

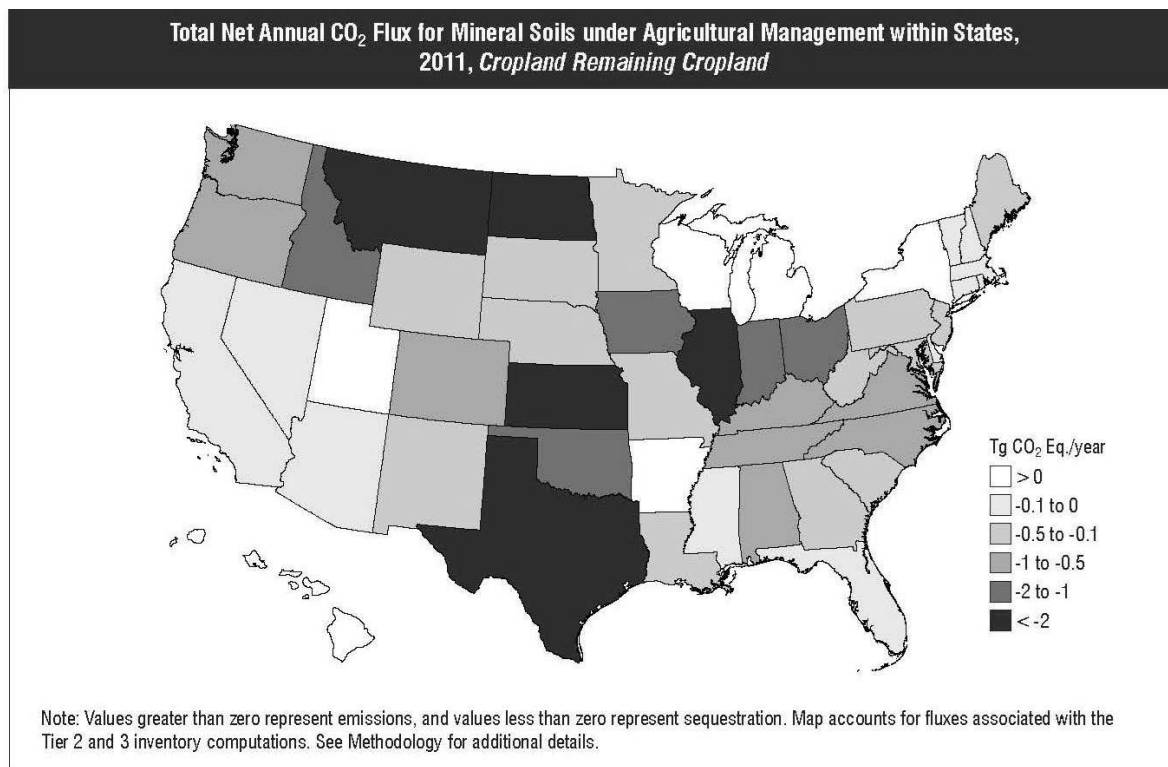
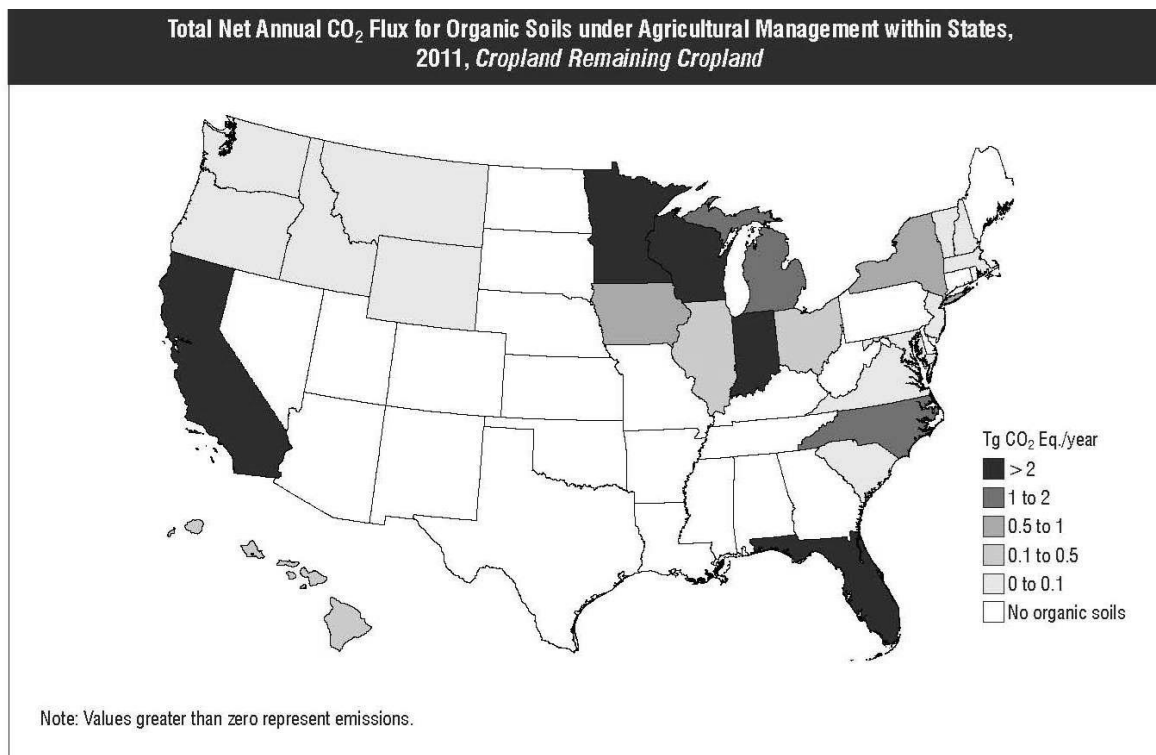


Figure 7-6: Total Net Annual CO₂ Flux for Organic Soils under Agricultural Management within States, 2011, *Cropland Remaining Cropland*



Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks due to: (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils for *Cropland Remaining Cropland*.

Soil C stock changes were estimated for *Cropland Remaining Cropland* (as well as agricultural land falling into the IPCC categories *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*) according to land-use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2009). The NRI is a statistically-based sample of all non-federal land, and includes approximately 529,558 points in agricultural land for the conterminous United States and Hawaii.²³² Each point is associated with an “expansion factor” that allows scaling of C stock changes from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. For cropland, data were collected for 4 out of 5 years in the cycle (i.e., 1979-1982, 1984-1987, 1989-1992, and 1994-1997). However, the NRI program began collecting annual data in 1998, and data are currently available through 2007. NRI points were classified as *Cropland Remaining Cropland* in a given year between 1990 and 2007 if the land use had been cropland for 20 years.²³³ Cropland includes all land used to produce food and fiber, or forage that is harvested and used as feed (e.g., hay and silage).

²³² NRI points were classified as agricultural if under grassland or cropland management between 1990 and 2007.

²³³ NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification prior to 2002 was based on less than 20 years of recorded land-use history for the time series.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach was applied to estimate C stock changes for mineral soils used to produce a majority of annual crops in the United States (Ogle et al. 2010), including alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. The model-based approach uses the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil C stock changes and soil nitrous oxide emissions from agricultural soil management. Carbon and N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N₂O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions are taken into account between C and N cycling in soils.

The remaining crops on mineral soils were estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, tobacco, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method was also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). Mineral SOC stocks were estimated using a Tier 2 method for these areas because the DAYCENT model, which is used for the Tier 3 method, has not been fully tested to address its adequacy for estimating C stock changes associated with certain crops and rotations, as well as cobbly, gravelly, or shaley soils. An additional stock change calculation was made for mineral soils using Tier 2 emission factors, accounting for enrollment patterns in the Conservation Reserve Program after 2007, which was not addressed by the Tier 3 method.

Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described below and in Annex 3.11.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates the dynamics of C and other elements in cropland, grassland, forest, and savanna ecosystems. The DAYCENT model utilizes the soil C modeling framework developed in Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Crop production is simulated with NASA-CASA production algorithm (Potter et al. 1993, Potter et al. 2007) using the MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, with a pixel resolution of 250m. A prediction algorithm was developed to estimate EVI (Gurung et al. 2009) for gap-filling during years over the inventory time series when EVI data were not available (e.g., data from the MODIS sensor were only available 2000 following the launch of the Aqua and Terra Satellites). The modeling approach uses daily weather data as an input, along with information about soil physical properties. Input data on land use and management are specified at a daily resolution and include land-use type, crop/forage type, and management activities (e.g., planting, harvesting, fertilization, manure amendments, tillage, irrigation, residue removal, grazing, and fire). The model computes net primary productivity and C additions to soil, soil temperature, and water dynamics, in addition to turnover, stabilization, and mineralization of soil organic matter C and nutrient (N, P, K, S) elements. This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC, because the simulation model treats changes as continuous over time rather than the simplified discrete changes represented in the default method (see Box 7-3 for additional information). National estimates were obtained by simulating historical land-use and management patterns as recorded in the USDA National Resources Inventory (NRI) survey.

Box 7-3: Tier 3 Approach for Soil C Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil C stock changes on the majority of agricultural land with mineral soils. This approach entails several fundamental differences compared to the IPCC Tier 1 or 2 methods, which classify land areas into a number of discrete classes based on a highly aggregated classification of climate, soil, and management (i.e., only six climate regions, seven soil types and eleven management systems occur in U.S. agricultural land under the IPCC classification). Input variables to the Tier 3 model, including climate, soils, and management activities (e.g., fertilization, crop species, tillage, etc.), are represented in considerably more detail both temporally and spatially, and exhibit multi-dimensional interactions through the more complex model structure compared with the IPCC Tier 1 or 2 approach. The spatial resolution of the analysis is also finer in the Tier 3

method compared to the lower tier methods as implemented in the United States for previous Inventories (e.g., 3,037 counties versus 181 Major Land Resource Areas (MLRAs), respectively).

The Tier 3 model simulates a continuous time period rather than the equilibrium step change used in the IPCC methodology (Tier 1 and 2). More specifically, the DAYCENT model (i.e., daily time-step version of the Century model) simulates soil C dynamics (and CO₂ emissions and uptake) on a daily time step based on C emissions and removals resulting from plant production and decomposition processes. The changes in soil C stocks are influenced by not only changes in land use and management but also weather variability and secondary feedbacks between management activities, climate, and soils, as they affect primary production and decomposition. This latter characteristic constitutes one of the greatest differences between the methods, and forms the basis for a more complete accounting of soil C stock changes in the Tier 3 approach compared with Tier 2 methodology. Consequently, delayed responses can occur due to variable weather patterns and other environmental constraints that interact with land use and management and affect the time frame over which stock changes occur in response to management decisions.

Additional sources of activity data were used to supplement the land-use information from NRI. The Conservation Technology Information Center (CTIC 2004) provided annual data on tillage activity at the county level since 1989, with adjustments for long-term adoption of no-till agriculture (Towery 2001). Information on fertilizer use and rates by crop type for different regions of the United States were obtained primarily from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to cropland during 1997 were estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 were used to adjust the area amended with manure (see Annex 3.11 for further details). Greater availability of managed manure N relative to 1997 was, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area. Data on the county-level N available for application were estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and including the addition of N from bedding materials. Nitrogen losses include direct N₂O emissions, volatilization of ammonia and NO_x, runoff and leaching, and poultry manure used as a feed supplement. For unmanaged systems, it is assumed that no N losses or additions occur prior to the application of manure to the soil. More information on livestock manure production is available in the Manure Management, Section 6.2, and Annex 3.10.

Daily weather data were used as an input in the model simulations, based on gridded weather data at a 32 km scale from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). Soil attributes were obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). The carbon dynamics at each NRI point was simulated 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulation runs for the analysis. Carbon stock estimates from DAYCENT were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Ogle et al. 2007, 2010). Carbon stocks and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but C stock changes from 2008 to 2011 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years.

Tier 2 Approach

In the IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity were used to classify land area to apply appropriate stock change factors. MLRAs formed the base spatial unit for mapping climate regions in the United States; each MLRA represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981). MLRAs were classified into climate regions according to the IPCC categories using the PRISM climate database of Daly et al. (1994).

Reference C stocks were estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2003, 2006). Changing the reference condition was necessary because soil measurements under agricultural management are

much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than native reference conditions.

U.S.-specific stock change factors were derived from published literature to determine the impact of management practices on SOC storage, including changes in tillage, cropping rotations and intensification, and land-use change between cultivated and uncultivated conditions (Ogle et al. 2003, Ogle et al. 2006). U.S. factors associated with organic matter amendments were not estimated because there were an insufficient number of studies to analyze those impacts. Instead, factors from IPCC (2003) were used to estimate the effect of those activities.

Activity data were primarily based on the historical land-use/management patterns recorded in the NRI. Each NRI point was classified by land use, soil type, climate region (using PRISM data, Daly et al. 1994) and management condition. Classification of cropland area by tillage practice was based on data from the Conservation Technology Information Center (CTIC 2004, Towery 2001) as described above. Activity data on wetland restoration of Conservation Reserve Program land were obtained from Euliss and Gleason (2002). Manure N amendments over the inventory time period were based on application rates and areas amended with manure N from Edmonds et al. (2003), in addition to the managed manure production data discussed in the previous methodology subsection on the Tier 3 analysis for mineral soils.

Combining information from these data sources, SOC stocks for mineral soils were estimated 50,000 times for 1982, 1992, 1997, 2002 and 2007, using a Monte Carlo stochastic simulation approach and probability distribution functions for U.S.-specific stock change factors, reference C stocks, and land-use activity data (Ogle et al. 2002, Ogle et al. 2003, Ogle et al. 2006). The annual C flux for 1990 through 1992 was determined by calculating the average annual change in stocks between 1982 and 1992; annual C flux for 1993 through 1997 was determined by calculating the average annual change in stocks between 1992 and 1997; annual C flux for 1998 through 2002 was determined by calculating the average annual change in stocks between 1998 and 2002; and annual C flux from 2003 through 2011 was determined by calculating the average annual change in stocks between 2003 and 2007.

Additional Mineral C Stock Change

Annual C flux estimates for mineral soils between 2008 and 2011 were adjusted to account for additional C stock changes associated with gains or losses in soil C after 2007 due to changes in Conservation Reserve Program enrollment. The change in enrollment acreage relative to 2007 was based on data from USDA-FSA (2012) for 2008 through 2011, and the differences in mineral soil areas were multiplied by 0.5 metric tons C per hectare per year to estimate the net effect on soil C stocks. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.11 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates included a measure of uncertainty as determined from the Monte Carlo Stochastic Simulation with 50,000 iterations. Emissions were based on the 1992, 1997, 2002 and 2007 *Cropland Remaining Cropland* areas from the 2007 *National Resources Inventory* (USDA-NRCS 2009). The annual emissions estimated for 1992 was applied to 1990 through 1992; annual emissions estimated for 1997 was applied to 1993 through 1997; annual emissions estimated for 2002 was applied to 1998 through 2002; and annual emissions estimated for 2007 was applied to 2003 through 2011.

Uncertainty and Time-Series Consistency

Uncertainty associated with the *Cropland Remaining Cropland* land-use category was addressed for changes in agricultural soil C stocks (including both mineral and organic soils). Uncertainty estimates are presented in Table 7-20 for each subsource (mineral soil C stocks and organic soil C stocks) and method that was used in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.11 for further discussion). Uncertainty estimates from each approach were combined using the error propagation equation in accordance with IPCC (2006). The combined uncertainty was calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. More details on how the individual uncertainties were developed are in Annex 3.11. The combined uncertainty for soil C stocks in *Cropland Remaining Cropland* ranged from 1160

percent below to 596 percent above the 2011 stock change estimate of 2.9 Tg CO₂ Eq. The large relative uncertainty is due to the small net flux estimate in 2011.

Table 7-20: Tier 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (Tg CO₂ Eq. and Percent)

Source	2011 Flux Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Flux Estimate			
		(Tg CO ₂ Eq.)	(%)		
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology*	(30.6)	(62.3)	(19.0)	-104%	38%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(2.8)	(5.1)	(0.9)	-80%	68%
Mineral Soil C Stocks: Cropland Remaining Cropland (Change in CRP enrollment relative to 2003)	3.7	1.9	5.6	-50%	50%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	26.8	17.7	39.0	-34%	46%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	(2.9)	(36.0)	14.2	-1160%	596%

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2011. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Methodological recalculations in this year's inventory were associated with the following improvements: 1) use of the DAYCENT biogeochemical model to estimate SOC stock changes for the Tier 3 method; 2) incorporation of MODIS Enhanced Vegetation Index to estimate crop production and subsequent C input to the soil; 3) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 4) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; 5) extension of the tillage activity dataset with statistics from Conservation Technology and Information Center (CTIC 2004); 6) including more crops in the Tier 3 method application that had been part of the Tier 2 method in the previous Inventory (i.e., dry beans, onions, peanuts, potatoes, rice, sugar beets, sunflowers, and tomatoes); and 7) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2011). SOC stock changes declined by 2.1 Tg CO₂ eq. on average over the time series as a result of these improvements in the Inventory. The largest changes in SOC trends tended to occur after 2002, and are attributed to the new NRI and tillage data (the previous Inventory was based on a time series of activity data that ended in 2003). However, improved estimation of C dynamics associated with the new DAYCENT model also had a significant effect on the recalculation for *Cropland Remaining Cropland*.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data were properly handled throughout the inventory process. DAYCENT simulations had errors in crop harvest indices that were corrected. Inventory reporting forms and text were reviewed and revised as needed to correct transcription errors. One of the key quality control issues was an under-estimation of C stocks in the DAYCENT model due to higher than expected decomposition rates. The model was re-parameterized to correct this error and accurately represent soil C dynamics. As discussed in the uncertainty section, results were compared to field measurements, and a

statistical relationship was developed to assess uncertainties in the model's predictive capability. The comparisons included over 45 long-term experiments, representing about 800 combinations of management treatments across all of the sites (Ogle et al. 2007) (See Annex 3.11 for more information).

Planned Improvements

An automated quality assurance/quality control system is currently under development for the Tier 3 method that is used to estimate the majority of emissions associated with this source category. Currently, quality control is conducted by manual graphing and queries to determine if values are outside of an expected range. The new system will automatically create graphs, maps and conduct range checking to improve efficiency in this important step for the inventory analysis. This development will ensure a more thorough review of the inventory results.

CO₂ Emissions from Agricultural Liming

IPCC (2006) recommends reporting CO₂ emissions from lime additions (in the form of crushed limestone (CaCO₃) and dolomite (CaMg(CO₃)₂) to agricultural soils. Limestone and dolomite are added by land managers to ameliorate acidification. When these compounds come in contact with acid soils, they degrade, thereby generating CO₂. The rate and ultimate magnitude of degradation of applied limestone and dolomite depends on the soil conditions, climate regime, and the type of mineral applied. Emissions from liming have fluctuated over the past nineteen years, ranging from 3.7 Tg CO₂ Eq. to 5.0 Tg CO₂ Eq. In 2011, liming of agricultural soils in the United States resulted in emissions of 4.5 Tg CO₂ Eq. (1.2 Tg C), representing about a 5 percent decrease in emissions since 1990 (see Table 7-21 and Table 7-22). The trend is driven entirely by the amount of lime and dolomite estimated to have been applied to soils over the time period.

Table 7-21: Emissions from Liming of Agricultural Soils (Tg CO₂ Eq.)

Source	1990	2005	2007	2008	2009	2010	2011
Liming of Soils ^a	4.7	4.3	4.5	5.0	3.7	4.7	4.5

^a Also includes emissions from liming on *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, and *Settlements Remaining Settlements*.

Table 7-22: Emissions from Liming of Agricultural Soils (Tg C)

Source	1990	2005	2007	2008	2009	2010	2011
Liming of Soils ^a	1.3	1.2	1.2	1.4	1.0	1.3	1.2

^a Also includes emissions from liming on *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, and *Settlements Remaining Settlements*.

Methodology

CO₂ emissions from degradation of limestone and dolomite applied to agricultural soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite applied (see Table 7-23) were multiplied by CO₂ emission factors from West and McBride (2005). These emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors because they account for the portion of agricultural lime that may leach through the soil and travel by rivers to the ocean (West and McBride 2005). This analysis of lime dissolution is based on liming occurring in the Mississippi River basin, where the vast majority of all U.S. liming takes place (West 2008). U.S. liming that does not occur in the Mississippi River basin tends to occur under similar soil and rainfall regimes, and, thus, the emission factor is appropriate for use across the United States (West 2008). The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Industry Surveys* (Tepordei 1993 through 2006; Willett 2007a, b, 2009 through 2011b; USGS 2008 through

2012). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying crushed stone manufacturers. Because some manufacturers were reluctant to provide information, the estimates of total crushed limestone and dolomite production and use were divided into three components: (1) production by end-use, as reported by manufacturers (i.e., “specified” production); (2) production reported by manufacturers without end-uses specified (i.e., “unspecified” production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., “estimated” production).

The “unspecified” and “estimated” amounts of crushed limestone and dolomite applied to agricultural soils were calculated by multiplying the percentage of total “specified” limestone and dolomite production applied to agricultural soils by the total amounts of “unspecified” and “estimated” limestone and dolomite production. In other words, the proportion of total “unspecified” and “estimated” crushed limestone and dolomite that was applied to agricultural soils (as opposed to other uses of the stone) was assumed to be proportionate to the amount of “specified” crushed limestone and dolomite that was applied to agricultural soils. In addition, data were not available for 1990, 1992, and 2011 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of “total crushed stone produced or used” reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2011 data, 2010 fractions were applied to a 2011 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2012* (USGS 2012); thus, the 2011 data in Table 7-21 through Table 7-23 are shaded to indicate that they are based on a combination of data and projections.

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the USGS from 1995 to the present. In 1994, the “Crushed Stone” chapter in the *Minerals Yearbook* began rounding (to the nearest thousand metric tons) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations. Since limestone and dolomite activity data are also available at the state level, the national-level estimates reported here were broken out by state, although state-level estimates are not reported here.

Table 7-23: Applied Minerals (Million Metric Tons)

Mineral	1990	2005	2007	2008	2009	2010	2011
Limestone	19.01	18.09	17.46	20.46	15.66	20.05	19.05
Dolomite	2.36	1.85	2.92	2.55	1.20	1.50	1.42

Note: Data represent amounts applied to *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, and Settlements Remaining Settlements*.

Uncertainty and Time-Series Consistency

Uncertainty regarding limestone and dolomite activity data inputs was estimated at ± 15 percent and assumed to be uniformly distributed around the inventory estimate (Tepordei 2003b). Analysis of the uncertainty associated with the emission factors included the following: the fraction of agricultural lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not accounted for, but should not change the uncertainty associated with CO₂ emissions (West 2005). The uncertainties associated with the fraction of agricultural lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were each modeled as a smoothed triangular distribution between ranges of zero percent to 100 percent. The uncertainty surrounding these two components largely drives the overall uncertainty estimates reported below. More information on the uncertainty estimates for Liming of Agricultural Soils is contained within the Uncertainty Annex.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO₂ emissions from liming. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-24. Carbon dioxide emissions from Liming of Agricultural Soils in 2011 were estimated to be between 0.25 and 9.24 Tg CO₂ Eq. at the 95 percent

confidence level. This indicates a range of 94 percent below to 112 percent above the 2011 emission estimate of 4.5 Tg CO₂ Eq.

Table 7-24: Tier 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Liming of Agricultural Soils (Tg CO₂ Eq. and Percent)

Source	Gas	2011 Emission Estimate	Uncertainty Range Relative to Emissions Estimate ^a			
		(Tg CO ₂ Eq.)	(Tg CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming of Agricultural Soils ¹	CO ₂	4.5	0.3	9.2	-94%	+112%

^aRange of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

¹ Also includes emissions from liming on *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, and *Settlements Remaining Settlements*.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2011. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

Several adjustments were made in the current Inventory to improve the results. The quantity of applied minerals reported in the previous Inventory for 2009 has been revised; the updated activity data for 2009 for limestone are approximately 76 thousand metric tons greater and the 2009 data for dolomite are approximately 110 thousand metric tons less than the data used for the previous Inventory. Consequently, the reported emissions resulting from liming in 2009 decreased by about 0.8 percent. In the previous Inventory, to estimate 2010 data, 2009 fractions were applied to a 2010 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2011* (USGS 2011). Since publication of the previous Inventory, the *Minerals Yearbook* has published actual quantities of crushed stone sold or used by producers in the United States in 2010. These values have replaced those used in the previous Inventory to calculate the quantity of minerals applied to soil and the emissions from liming. The updated activity data for 2011 are approximately 3,605 thousand metric tons greater than the data used in the previous Inventory. As a result, the reported emissions from liming in 2010 increased by about 20 percent.

CO₂ Emissions from Urea Fertilization

The use of urea (CO(NH₂)₂) as fertilizer leads to emissions of CO₂ that was fixed during the industrial production process. Urea in the presence of water and urease enzymes is converted into ammonium (NH₄⁺), hydroxyl ion (OH⁻), and bicarbonate (HCO₃⁻). The bicarbonate then evolves into CO₂ and water. Emissions from urea fertilization in the United States totaled 3.7 Tg CO₂ Eq. (1.0 Tg C) in 2011 (Table 7-25 and Table 7-26). Emissions from urea fertilization have grown 52 percent between 1990 and 2011, due to an increase in the use of urea as fertilizer.

Table 7-25: CO₂ Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg CO₂ Eq.)

Source	1990	2005	2007	2008	2009	2010	2011
Urea Fertilization ^a	2.4	3.5	3.8	3.6	3.6	3.7	3.7

^a Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, and Forest Land Remaining Forest Land*.

Table 7-26: CO₂ Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg C)

Source	1990	2005	2007	2008	2009	2010	2011
Urea Fertilization ^a	0.7	1.0	1.0	1.0	1.0	1.0	1.0

^a Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, and Forest Land Remaining Forest Land*.

Methodology

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The annual amounts of urea fertilizer applied (see Table 7-27) were derived from state-level fertilizer sales data provided in *Commercial Fertilizers* (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2011b) and were multiplied by the default IPCC (2006) emission factor of 0.20, which is equal to the C content of urea on an atomic weight basis. Because fertilizer sales data are reported in fertilizer years (July through June), a calculation was performed to convert the data to calendar years (January through December). According to historic monthly fertilizer use data (TVA 1992b), 65 percent of total fertilizer used in any fertilizer year is applied between January and June of that calendar year, and 35 percent of total fertilizer used in any fertilizer year is applied between July and December of the previous calendar year. Fertilizer sales data for the 2011 fertilizer year were not available in time for publication. Accordingly, urea application in the 2011 fertilizer year was assumed to be equal to that of the 2010 fertilizer year. Since 2012 fertilizer year data were not available, July through December 2011 fertilizer consumption was estimated by calculating the percent change in urea use from January through June 2010 to January through June 2011. For this Inventory, because fertilizer year 2011 activity data were set equal to 2010 activity data, this percent change was zero. This percent change was then multiplied by the July through December 2010 data to estimate July through December 2011 fertilizer use; thus, the 2011 data in Table 7-25 through Table 7-27 are shaded to indicate that they are based on a combination of data and projections. State-level estimates of CO₂ emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States.

Table 7-27: Applied Urea (Million Metric Tons)

	1990	2005	2007	2008	2009	2010	2011
Urea Fertilizer ¹	3.30	4.78	5.12	4.93	4.86	4.99	4.99

¹These numbers represent amounts applied to all agricultural land, including *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, and Forest Land Remaining Forest Land*.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 7-28 for Urea Fertilization. A Tier 2 Monte Carlo analysis was completed. The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C applied to soils is ultimately emitted into the environment as CO₂. This factor does not incorporate the possibility that some of the C may be retained in the soil. The emission estimate is, therefore, likely to be high. In addition, each urea consumption data point has an associated uncertainty. Urea for non-fertilizer use, such as aircraft deicing, may be included in consumption totals; it was determined through personal communication with Fertilizer Regulatory Program Coordinator David L. Terry (2007), however, that this amount is most likely very small.

Research into aircraft deicing practices also confirmed that urea is used minimally in the industry; a 1992 survey found a known annual usage of approximately 2,000 tons of urea for deicing; this would constitute 0.06 percent of the 1992 consumption of urea (EPA 2000). Similarly, surveys conducted from 2002 to 2005 indicate that total urea use for deicing at U.S. airports is estimated to be 3,740 MT per year, or less than 0.07 percent of the fertilizer total for 2007 (Itle 2009). Lastly, there is uncertainty surrounding the assumptions behind the calculation that converts fertilizer years to calendar years. Carbon dioxide emissions from urea fertilization of agricultural soils in 2011 were estimated to be between 2.1 and 3.8 Tg CO₂ Eq. at the 95 percent confidence level. This indicates a range of 42 percent below to 4 percent above the 2011 emission estimate of 3.7 Tg CO₂ Eq.

Table 7-28: Quantitative Uncertainty Estimates for CO₂ Emissions from Urea Fertilization (Tg CO₂ Eq. and Percent)

Source	Gas	2011 Emission Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emissions Estimate ^a			
			(Tg CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO ₂	3.7	2.1	3.8	-42%	+4%

^aRange of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: These numbers represent amounts applied to all agricultural land, *including Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, and Forest Land Remaining Forest Land.*

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2011. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. Inventory reporting forms and text were reviewed. No errors were found.

Recalculations Discussion

In the current Inventory, July to December 2010 urea application data were updated with assumptions for fertilizer year 2011, and the 2010 emission estimate was revised accordingly. The activity data decreased by about 655,000 metric tons for 2010 and this change resulted in an approximately 11.6 percent decrease in emissions in 2010 relative to the previous Inventory.

Planned Improvements

The primary planned improvement is to investigate using a Tier 2 or Tier 3 approach, which would utilize country-specific information to estimate a more precise emission factor.

7.5 Land Converted to Cropland (IPCC Source Category 5B2)

Land Converted to Cropland includes all cropland in an inventory year that had been another land use at any point during the previous 20 years according to the USDA NRI land-use survey (USDA-NRCS 2009).²³⁴ Consequently, lands are retained in this category for 20 years as recommended by the IPCC guidelines (IPCC 2006) unless there is another land-use change. The inventory includes all privately-owned croplands in the conterminous United States and Hawaii, but there is a minor amount of cropland on federal lands that is not currently included in the estimation of C stock changes, leading to a discrepancy between the total amount of managed area in *Land Converted to Cropland* (see Section 7.1) and the cropland area included in the inventory.

Background on agricultural C stock changes is provided in *Cropland Remaining Cropland* and will only be summarized here for *Land Converted to Cropland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils. The IPCC (2006) recommends reporting changes in SOC stocks due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.²³⁵

Land-use and management of mineral soils in *Land Converted to Cropland* led to losses of C throughout the time series (Table 7-29 and Table 7-30). The total rate of change in soil C stocks was 14.5 Tg CO₂ Eq. (4.0 Tg C) in 2011. Mineral soils were estimated to lose 13.4 Tg CO₂ Eq. (3.6 Tg C) in 2011, while drainage and cultivation of organic soils led to an annual loss of 1.1 Tg CO₂ Eq. (0.3 Tg C) in 2011.

Table 7-29: Net CO₂ Flux from Soil C Stock Changes in Land Converted to Cropland (Tg CO₂ Eq.)

Soil Type	1990	2005	2007	2008	2009	2010	2011
Mineral Soils	18.9	12.4	13.4	13.4	13.4	13.4	13.4
Organic Soils	2.2	1.1	1.1	1.1	1.1	1.1	1.1
Total Net Flux	21.0	13.5	14.5	14.5	14.5	14.5	14.5

Table 7-30: Net CO₂ Flux from Soil C Stock Changes in Land Converted to Cropland (Tg C)

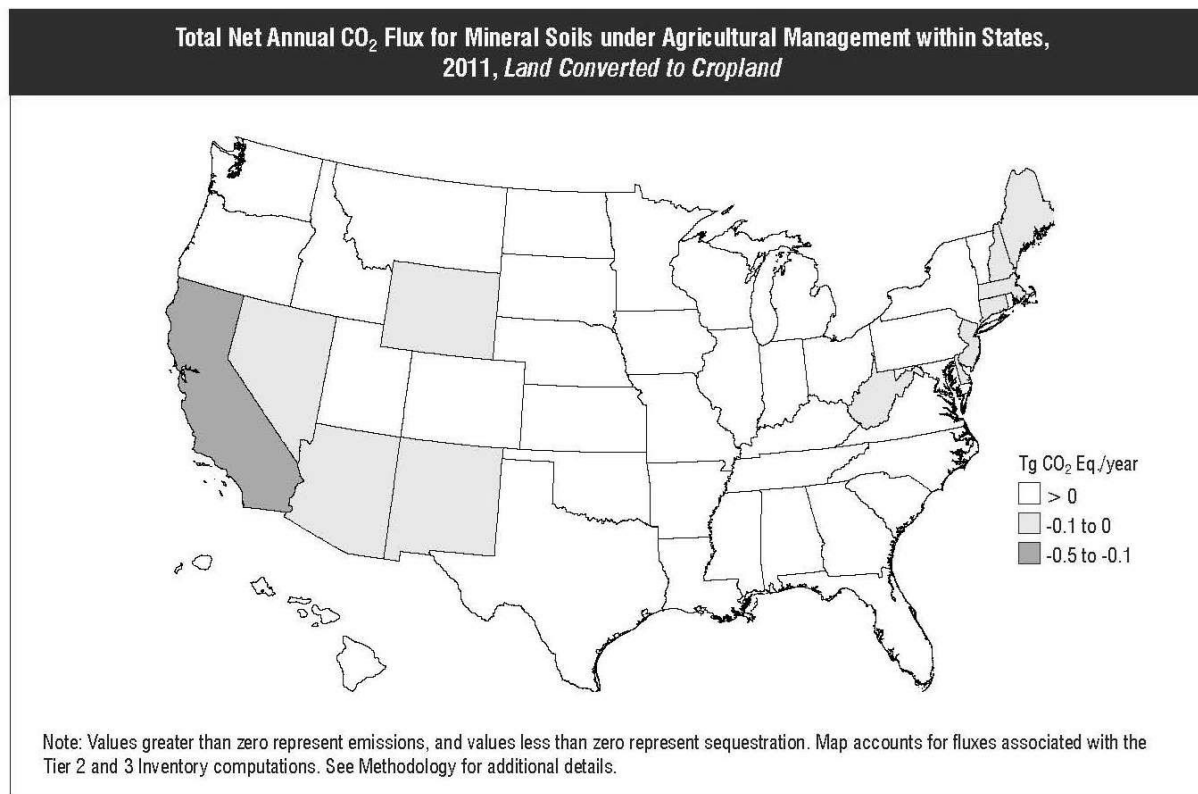
Soil Type	1990	2005	2007	2008	2009	2010	2011
Mineral Soils	5.1	3.4	3.6	3.6	3.6	3.6	3.6
Organic Soils	0.6	0.3	0.3	0.3	0.3	0.3	0.3
Total Net Flux	5.7	3.7	4.0	4.0	4.0	4.0	4.0

The spatial variability in 2011 annual CO₂ flux associated with C stock changes in mineral and organic soils for *Land Converted to Cropland* is displayed in Figure 7-7 and Figure 7-8. The largest losses occurred in the southwestern and Northeastern US. Conversion of grassland to cropland in these regions led to enhanced decomposition of soil organic matter with cultivation and a net loss of carbon from the soil. Emissions from organic soils were largest in the Southeastern Coastal Region (particularly Florida), the upper Midwest and Northeast surrounding the Great Lakes, in addition to the Pacific Coastal Region, which coincides with areas that have a large concentration of cultivated organic soils in the United States.

²³⁴ NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications were based on less than 20 years from 1990 to 2001.

²³⁵ CO₂ emissions associated with liming are also estimated but included in 7.4 Cropland Remaining Cropland.

Figure 7-7: Total Net Annual CO₂ Flux for Mineral Soils under Agricultural Management within States, 2011, *Land Converted to Cropland*



Total Net Annual CO₂ Flux for Organic Soils under Agricultural Management within States, 2011, Land Converted to Cropland

Tg CO₂ Eq./year

- 0.5 to 1
- 0.1 to 0.5
- 0 to 0.1
- No organic soils

Note: Values greater than zero represent emissions.

The following section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral and organic soils for *Land Converted to Cropland*. Biomass C stock changes are not explicitly included in this category but biomass C losses associated with conversion of forest to grassland are included in the *Forest Land Remaining Forest Land* section. Further elaboration on the methodologies and data used to estimate stock changes for mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.11.

Mineral Soil Carbon Stock Changes

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(Ogle et al. 2003), including land used to produce some vegetables, tobacco, perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from forest or federal ownership.²³⁶

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the DAYCENT biogeochemical model for the Tier 3 method (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DAYCENT model utilizes the soil C modeling framework developed in Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. National estimates were obtained by using the model to simulate historical land-use change patterns as recorded in the USDA National Resources Inventory (USDA-NRCS 2009). C stocks and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but C stock changes from 2008 to 2011 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years. The methods used for *Land Converted to Cropland* are the same as those described in the Tier 3 portion of *Cropland Remaining Cropland* section for mineral soils (see *Cropland Remaining Cropland* Tier 3 methods section and Annex 3.11 for additional information).

Tier 2 Approach

For the mineral soils not included in the Tier 3 analysis, SOC stock changes were estimated using a Tier 2 Approach for *Land Converted to Cropland* as described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils (see *Cropland Remaining Cropland* Tier 2 methods section for additional information).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Cropland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), with U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils (see *Cropland Remaining Cropland* Organic Soils methods section and Annex 3.11 for additional information).

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches were based on the same method described for *Cropland Remaining Cropland*. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Cropland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 7-31 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) and method that was used in the Inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.11 for further discussion). Uncertainty estimates from each approach were combined using the error propagation equation in accordance with IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. More detail on how the individual uncertainties were estimated is in Annex 3.11. The combined uncertainty for soil C stocks in *Land Converted to Cropland* ranged from -70 percent below to 70 percent above the 2011 stock change estimate of 14.5 Tg CO₂ Eq.

Table 7-31: Tier 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Cropland* (Tg CO₂ Eq. and Percent)

Source	2011 Flux Estimate	Uncertainty Range Relative to Flux Estimate

²³⁶ Federal land is not a land use, but rather an ownership designation that is treated as forest or nominal grassland for purposes of these calculations. The specific use for federal lands is not identified in the NRI survey (USDA-NRCS 2009).

	(Tg CO ₂ Eq.)	(Tg CO ₂ Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Land Converted to Cropland, Tier 3 Inventory Methodology	11.8	1.8	21.9	-85%	85%
Mineral Soil C Stocks: Land Converted to Cropland, Tier 2 Inventory Methodology	1.5	0.8	2.4	-49%	54%
Organic Soil C Stocks: Land Converted to Cropland, Tier 2 Inventory Methodology	1.1	0.3	2.2	-71%	94%
Combined Uncertainty for Flux associated with Soil Carbon Stock Change in Land Converted to Cropland	14.5	4.4	24.7	-70%	70%

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2011. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Methodological recalculations in the current Inventory were associated with the following improvements: 1) use of the DAYCENT biogeochemical model to estimate SOC stock changes for the Tier 3 method; 2) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 3) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; 4) extension of the tillage activity dataset with statistics from Conservation Technology and Information Center (CTIC 2004); 5) including more crops in the Tier 3 method application that had been part of the Tier 2 method in the previous Inventory (i.e., dry beans, onions, peanuts, potatoes, rice, sugar beets, sunflowers, and tomatoes); and 6) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2009). SOC change rates declined by 13.7 Tg CO₂ eq. on average over the time series as a result of these improvements to the Inventory. Improved estimation of C dynamics associated with the new DAYCENT model had the largest influence on the recalculation for *Land Converted to Cropland*.

QA/QC and Verification

See QA/QC and Verification section under *Cropland Remaining Cropland*.

Planned Improvements

Soil C stock changes with land use conversion from forest land to cropland are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and croplands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to cropland. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.6 Grassland Remaining Grassland (IPCC Source Category 5C1)

Grassland Remaining Grassland includes all grassland in an inventory year that had been grassland for the previous 20 years²³⁷ according to the USDA NRI land use survey (USDA-NRCS 2009). The inventory includes all privately-owned grasslands in the conterminous United States and Hawaii, but does not address changes in C stocks for grasslands on federal lands, leading to a discrepancy between the total amount of managed area in *Grassland Remaining Grassland* (see Section 7.1) and the grassland area included in the Inventory. While federal grasslands probably have minimal changes in land management and C stocks, plans are being made to further evaluate and potentially include these areas in future C inventories.

Background on agricultural C stock changes is provided in the *Cropland Remaining Cropland* section and will only be summarized here for *Grassland Remaining Grassland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared to soils. IPCC (2006) recommends reporting changes in SOC stocks due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.²³⁸

Land-use and management increased soil C in mineral soils of *Grassland Remaining Grassland* until 2007 when the trend was reversed to small decreases in soil C. Organic soils lost relatively small amounts of C in each year 1990 through 2011. Due to the pattern for mineral soils, the overall trend was a gain in soil C through most of the time series, except for the last few years of the time series where there were small losses. The rates varied from year to year but there was a net emission of 7.4 Tg CO₂ Eq. (2.0 Tg C) in 2011. There was considerable variation over the time series driven by variability in weather patterns and associated interaction with land management activity. The change rates on per hectare basis were small, however, even in the years with larger total changes in stocks. Overall, flux rates declined by 12.7 Tg CO₂ Eq. (3.5 Tg C) when comparing the net change in soil C from 1990 and 2011.

Table 7-32: Net CO₂ Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (Tg CO₂ Eq.)

Soil Type	1990	2005	2007	2008	2009	2010	2011
Mineral Soils	(8.7)	(3.8)	4.4	4.4	4.5	4.6	4.6
Organic Soils	3.4	2.8	2.8	2.8	2.8	2.8	2.8
Total Net Flux	(5.3)	(1.0)	7.1	7.2	7.3	7.3	7.4

Note: Totals may not sum due to independent rounding.

Table 7-33: Net CO₂ Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (Tg C)

Soil Type	1990	2005	2007	2008	2009	2010	2011
Mineral Soils	(2.4)	(1.0)	1.2	1.2	1.2	1.2	1.3
Organic Soils	0.9	0.8	0.8	0.8	0.8	0.8	0.8
Total Net Flux	(1.4)	(0.3)	1.9	2.0	2.0	2.0	2.0

Note: Totals may not sum due to independent rounding.

The spatial variability in the 2011 annual CO₂ flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-9 and Figure 7-10. Grassland gained soil organic C in several regions during 2011, including the Northeast, Southwest, Midwest, Southwest and far western states; although the gains were relatively small on a

²³⁷ NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications were based on less than 20 years from 1990 to 2001.

²³⁸ CO₂ emissions associated with liming are also estimated but included in 7.4 Cropland Remaining Cropland.

per-hectare basis in most of these regions. Emission rates from drained organic soils were highest from organic soils were largest in the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeastern regions, in addition the Pacific Coastal Region, coinciding with largest concentrations of organic soils in the United States that are used for agricultural production.

Figure 7-9: Total Net Annual CO₂ Flux for Mineral Soils under Agricultural Management within States, 2011, *Grassland Remaining Grassland*

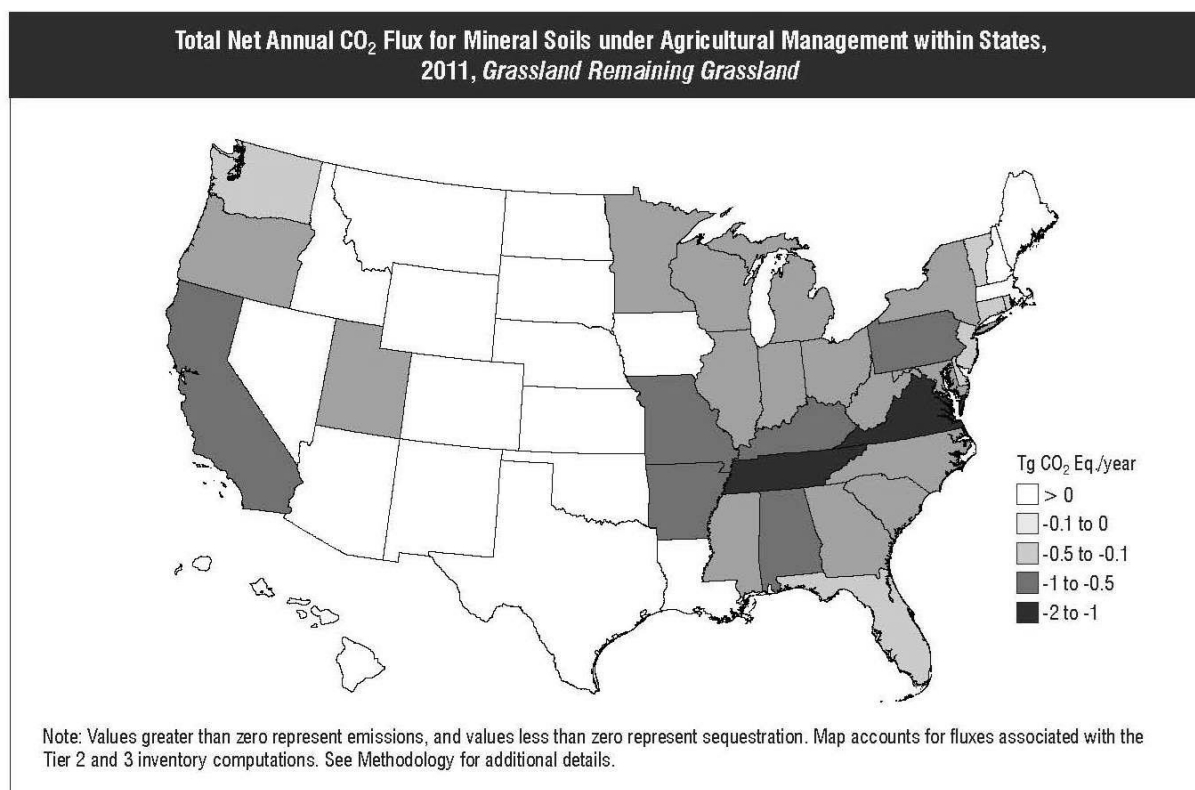
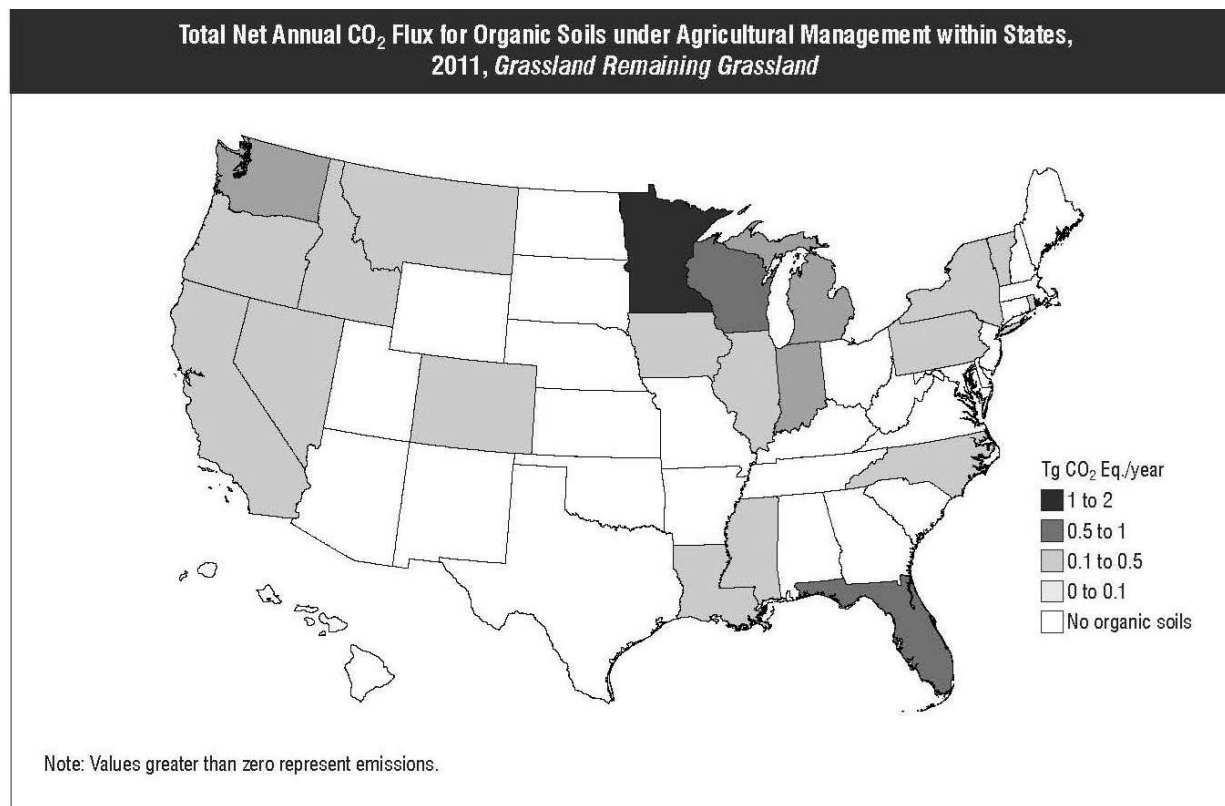


Figure 7-10: Total Net Annual CO₂ Flux for Organic Soils under Agricultural Management within States, 2011, *Grassland Remaining Grassland*



Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral and organic soils for *Grassland Remaining Grassland*. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.11.

Soil C stock changes were estimated for *Grassland Remaining Grassland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2009). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2007. NRI points were classified as *Grassland Remaining Grassland* in a given year between 1990 and 2007 if the land use had been grassland for 20 years. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are often seeded grassland, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach was applied to estimate C stock changes for most mineral soils in *Grassland Remaining Grassland*. The C stock changes for the remaining soils were estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume) and additional stock changes associated with sewage sludge amendments.

Tier 3 Approach

Mineral SOC stocks and stock changes for *Grassland Remaining Grassland* were estimated using the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in *Cropland Remaining Cropland*. The DAYCENT model utilizes the soil C modeling framework developed in Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land-use and management patterns were used in the DAYCENT simulations as recorded in the USDA National Resources Inventory (NRI) survey, with supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) and National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to grassland during 1997 were estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds, et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 were used to adjust the area amended with manure (see Annex 3.11 for further details). Greater availability of managed manure N relative to 1997 was, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area.

The amount of manure produced by each livestock type was calculated for managed and unmanaged waste management systems based on methods described in the Manure Management, Section 6.2, and Annex 3.10. Manure N deposition from grazing animals (i.e., PRP manure) was an input to the DAYCENT model (see Annex 3.10), and included approximately 91 percent of total PRP manure (the remainder is deposited on federal lands, which are currently not included in this inventory). C stocks and 95 percent confidence intervals were estimated for each year between 1990 and 2007, but C stock changes from 2008 to 2011 were assumed to be similar to 2007 because no additional activity data are currently available from the NRI for the latter years. See the Tier 3 methods in *Cropland Remaining Cropland* section for additional discussion on the Tier 3 methodology for mineral soils.

Tier 2 Approach

The Tier 2 approach is based on the same methods described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils (see *Cropland Remaining Cropland* Tier 2 methods section and Annex 3.11 for additional information).

Additional Mineral C Stock Change Calculations

Annual C flux estimates for mineral soils between 1990 and 2011 were adjusted to account for additional C stock changes associated with sewage sludge amendments using a Tier 2 method. Estimates of the amounts of sewage sludge N applied to agricultural land were derived from national data on sewage sludge generation, disposition, and N content. Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, were obtained from an EPA report (EPA 1999) and estimates for 2004 were obtained from an independent national biosolids survey (NEBRA 2007). These values were linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. N application rates from Kellogg et al. (2000) were used to determine the amount of area receiving sludge amendments. Although sewage sludge can be added to land managed for other land uses, it was assumed that agricultural amendments occur in grassland. Cropland is assumed to rarely be amended with sewage sludge due to the high metal content and other pollutants in human waste. The soil C storage rate was estimated at 0.38 metric tons C per hectare per year for sewage sludge amendments to grassland. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.11 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Emissions were based on the 1992, 1997, 2002 and 2007 *Grassland Remaining Grassland* areas from the 2007 *National Resources Inventory* (USDA-NRCS 2009). The annual emissions estimated for 1992 was applied to 1990 through 1992; annual emissions estimated for 1997 was applied to 1993 through 1997; annual emissions estimated for 2002 was applied to 1998 through 2002; and annual emissions estimated for 2007 was applied to 2003 through 2011.

Uncertainty and Time-Series Consistency

Uncertainty estimates are presented in Table 7-34 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.11 for further discussion). Uncertainty estimates from each approach were combined using the error propagation equation in accordance with IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. More details on how the individual uncertainties were developed are in Annex 3.11. The combined uncertainty for soil C stocks in *Grassland Remaining Grassland* ranged from 497 percent below to 497 percent above the 2011 stock change estimate of 7.4 Tg CO₂ Eq. The large relative uncertainty is due to the small net flux estimate in 2011.

Table 7-34: Tier 2 Quantitative Uncertainty Estimates for C Stock Changes Occurring Within *Grassland Remaining Grassland* (Tg CO₂ Eq. and Percent)

Source	2011 Flux Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Flux Estimate			
		(Tg CO ₂ Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks <i>Grassland Remaining Grassland</i> , Tier 3 Methodology	5.8	(31.1)	42.7	-636%	636%
Mineral Soil C Stocks: <i>Grassland Remaining Grassland</i> , Tier 2 Methodology	0.1	0.0	0.2	-86%	110%
Mineral Soil C Stocks: <i>Grassland Remaining Grassland</i> , Tier 2 Methodology (Change in Soil C due to Sewage Sludge Amendments)	(1.2)	(1.9)	(0.6)	-50%	50%
Organic Soil C Stocks: <i>Grassland Remaining Grassland</i> , Tier 2 Methodology	2.8	1.4	4.6	-48%	65%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in <i>Grassland Remaining Grassland</i>	7.4	(29.5)	44.4	-497%	497%

Note: Parentheses indicate negative values.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2011. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Methodological recalculations in the current Inventory were associated with the following improvements: 1) use of the DAYCENT biogeochemical model to estimate SOC stock changes for the Tier 3 method; 2) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 3) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; and 4) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2009). SOC stock change declined by 11.75 Tg CO₂ eq. on average over the time series as a result of these improvements in the Inventory. Improved estimation of C dynamics associated with the new DAYCENT model had the largest influence on the recalculation for *Grassland Remaining Grassland*.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data were properly handled through the inventory process. DAYCENT simulations had errors in the PRP manure N application during an initial set of simulations that were later corrected. Crop harvest indices also had errors that were corrected.

Inventory reporting forms and text were reviewed and revised as needed to correct transcription errors. Modeled results were compared to measurements from several long-term grazing experiments (See Annex 3.11 for more information). One of the key quality control issues was an under-estimation of C stocks in the DAYCENT model due to higher than expected decomposition rates. The model was re-parameterized to correct this error and accurately represent soil C dynamics.

Planned Improvements

One of the key planned improvements for the *Grassland Remaining Grassland* is to develop and inventory of carbon stock changes on federal grasslands in the western U.S. This is a significant improvement and will take several years to implement. See Planned Improvements section under *Cropland Remaining Cropland* for information about other upcoming improvements.

7.7 Land Converted to Grassland (IPCC Source Category 5C2)

Land Converted to Grassland includes all grassland in an inventory year that had been in another land use at any point during the previous 20 years²³⁹ according to the USDA NRI land-use survey (USDA-NRCS 2009). Consequently, lands are retained in this category for 20 years as recommended by IPCC (2006) unless there is another land use change. The Inventory includes all privately-owned grasslands in the conterminous United States and Hawaii, but does not address changes in C stocks for grasslands on federal lands, leading to a discrepancy between the total amount of managed area for *Land Converted to Grassland* (see Section 7.1) and the grassland area included in the Inventory. It is important to note that plans are being made to include these areas in future C inventories.

Background on agricultural C stock changes is provided in *Cropland Remaining Cropland* and will only be summarized here for *Land Converted to Grassland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils. IPCC (2006) recommend reporting changes in SOC stocks due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.²⁴⁰

Land-use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks from 1990 through 2011 (see Table 7-35 and Table 7-36). For example, the stock change rates were estimated to remove 7.7 Tg CO₂ Eq. (2.1 Tg C) and 8.8 Tg CO₂ Eq. (2.4 Tg C) from mineral soils in 1990 and 2011, respectively. Drainage of organic soils for grazing management led to losses varying from 0.4 to 0.8 Tg CO₂ Eq. yr⁻¹ (0.1 to 0.2 Tg C).

Table 7-35: Net CO₂ Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg CO₂ Eq.)

Soil Type	1990	2005	2007	2008	2009	2010	2011
Mineral Soils ^a	(8.1)	(11.0)	(9.8)	(9.8)	(9.7)	(9.6)	(9.6)
Organic Soils	0.4	0.8	0.8	0.8	0.8	0.8	0.8
Total Net Flux	(7.7)	(10.2)	(9.0)	(9.0)	(8.9)	(8.8)	(8.8)

²³⁹ NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications were based on less than 20 years from 1990 to 2001.

²⁴⁰ CO₂ emissions associated with liming are also estimated but included in 7.4 Cropland Remaining Cropland.

Table 7-36: Net CO₂ Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg C)

Soil Type	1990	2005	2007	2008	2009	2010	2011
Mineral Soils ^a	(2.2)	(3.0)	(2.7)	(2.7)	(2.6)	(2.6)	(2.6)
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Total Net Flux	(2.1)	(2.8)	(2.5)	(2.4)	(2.4)	(2.4)	(2.4)

The spatial variability in annual CO₂ flux associated with C stock changes in mineral soils is displayed in Figure 7-11 and Figure 7-12. Soil C stock increased in most states for *Land Converted to Grassland*. The largest gains were in the Southeastern region, Northeast, South-Central, Midwest, and northern Great Plains. The patterns were driven by conversion of annual cropland into continuous pasture. Emissions from organic soils were highest in the Pacific Coastal Region, Gulf Coast Region (particularly Florida), and the upper Midwest and Northeast surrounding the Great Lakes, coinciding with the largest concentrations of organic soils in the United States that are used for agricultural production.

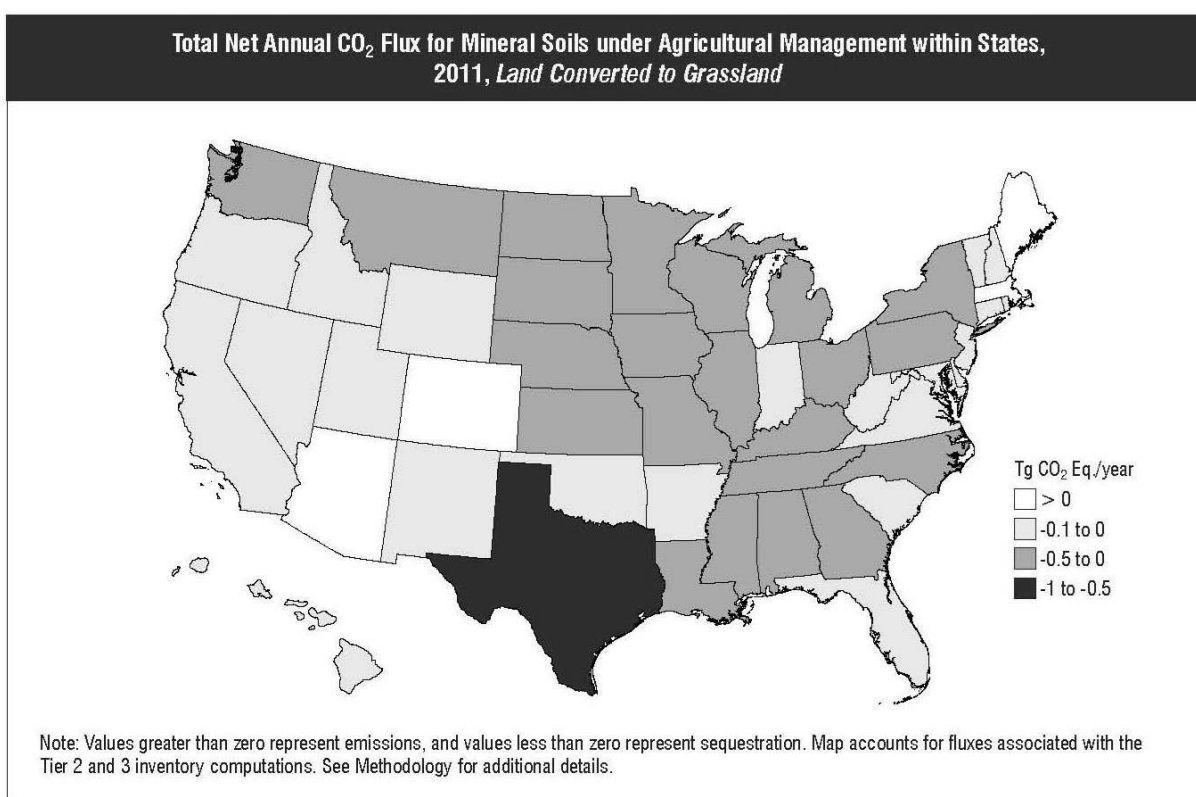
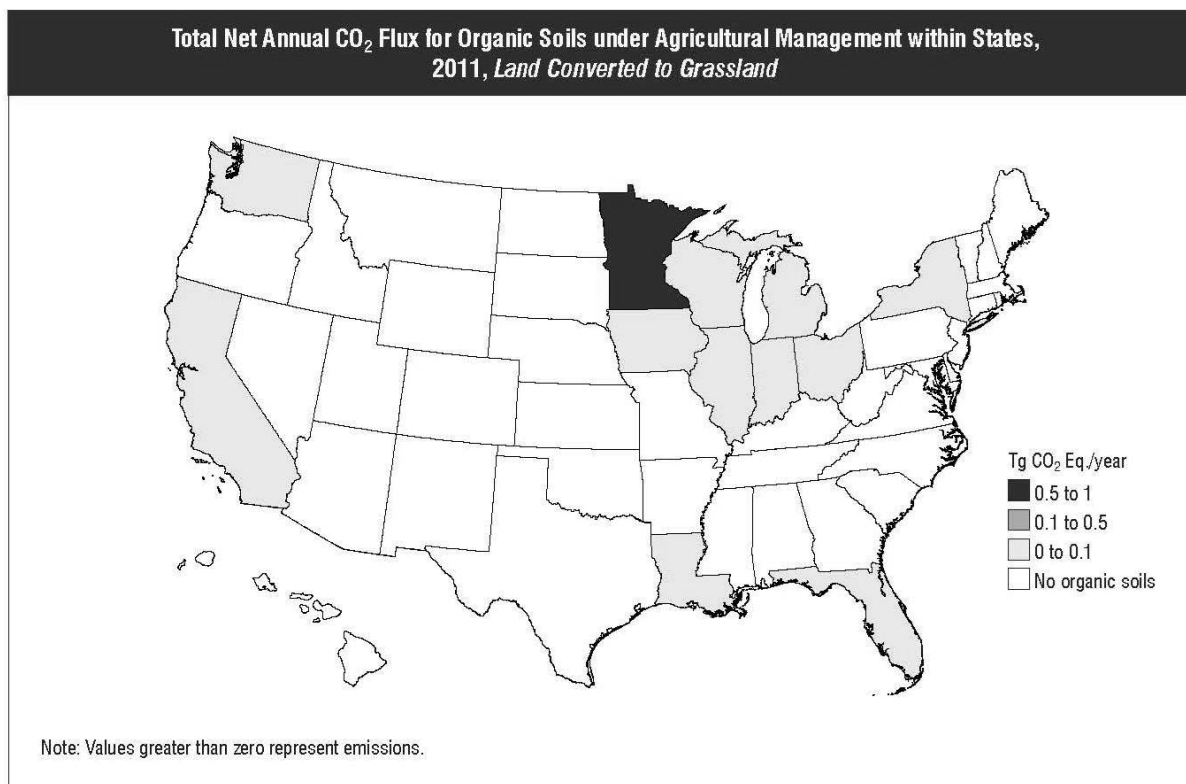
Figure 7-11: Total Net Annual CO₂ Flux for Mineral Soils under Agricultural Management within States, 2011, *Land Converted to Grassland*

Figure 7-12: Total Net Annual CO₂ Flux for Organic Soils under Agricultural Management within States, 2011, *Land Converted to Grassland*



Methodology

This section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral soils for *Land Converted to Grassland*. Biomass C stock changes are not explicitly included in this category but losses associated with conversion of forest to grassland are included in the *Forest Land Remaining Forest Land* section. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.11.

Soil C stock changes were estimated for *Land Converted to Grassland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2009). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2007. NRI points were classified as *Land Converted to Grassland* in a given year between 1990 and 2009 if the land use was grassland, but had been another use in the previous 20 years. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangeland typically includes extensive areas of native grassland that are not intensively managed, while pastures are often seeded grassland, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach was applied to estimate C stock changes for *Land Converted to Grassland* on most mineral soils. C stock changes on the remaining soils were estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, perennial/horticultural crops, and rice; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from

forest or federal ownership.²⁴¹ A Tier 2 approach was also used to estimate additional changes in mineral soil C stocks due to sewage sludge amendments. However, stock changes associated with sewage sludge amendments are reported in the *Grassland Remaining Grassland* section.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) as described for *Grassland Remaining Grassland*. The DAYCENT model utilizes the soil C modeling framework developed in Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land-use and management patterns were used in the DAYCENT simulations as recorded in the NRI survey, with supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) and the National Agricultural Statistics Service (NASS 1992, 1999, 2004) (see *Grassland Remaining Grassland* Tier 3 methods section and Annex 3.11 for additional information).

Tier 2 Approach

The Tier 2 approach used for *Land Converted to Grassland* on mineral soils is the same as described for *Cropland Remaining Cropland* (See *Cropland Remaining Cropland* Tier 2 Approach and Annex 3.11 for additional information).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Grassland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), with U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Grassland Remaining Grassland* section for organic soils (see *Cropland Remaining Cropland* Organic Soils methods section and Annex 3.11 for additional information).

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches were based on the same method described in *Cropland Remaining Cropland*. The uncertainty or annual C emission estimates from drained organic soils in *Land Converted to Grassland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 7-37 for each subsource (i.e., mineral soil C stocks and organic soil C stocks), disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.11 for further discussion). Uncertainty estimates from each approach were combined using the error propagation equation in accordance with IPCC (2006) (i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities). More detail on how the individual uncertainties were estimated is in Annex 3.11. The combined uncertainty for soil C stocks in *Land Converted to Grassland* ranged from -105 percent below to 105 percent above the 2011 stock change estimate of 8.8 Tg CO₂ Eq. The large relative uncertainty is due to the small net flux estimate in 2011.

Table 7-37: Tier 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Grassland* (Tg CO₂ Eq. and Percent)

Source	2011 Flux Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO ₂ Eq.)	(%)

²⁴¹ Federal land is not a land use, but rather an ownership designation that is treated as forest or nominal grassland for purposes of these calculations. The specific use for federal lands is not identified in the NRI survey (USDA-NRCS 2009).

		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Land Converted to Grassland, Tier 3 Inventory Methodology	(7.1)	(16.2)	2.0	-129%	129%
Mineral Soil C Stocks: Land Converted to Grassland, Tier 2 Inventory Methodology	(2.5)	(3.7)	(1.4)	-48%	44%
Organic Soil C Stocks: Land Converted to Grassland, Tier 2 Inventory Methodology	0.8	0.4	1.4	-51%	72%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stocks in Land Converted to Grassland	(8.8)	(18.0)	0.4	-105%	105%

Note: Parentheses indicate negative values.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2011. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Methodological recalculations in the current Inventory were associated with the following improvements: 1) use of the DAYCENT biogeochemical model to estimate SOC stock changes for the Tier 3 method; 2) incorporation of new activity data from the National Resources Inventory (NRI), extending the time series through 2007 (USDA-NRCS 2009); 3) recalculation of the Tier 2 portion of the inventory with the new NRI activity data; and 4) extension of the N fertilizer activity data with new USDA statistics on fertilizer use through 2009 (USDA-ERS 2009). SOC stock changes declined by 13.42 Tg CO₂ eq. on average over the time series as a result of these improvements in the Inventory. Improved estimation of C dynamics associated with the new DAYCENT model had the largest influence on the recalculation for *Land Converted to Grassland*.

QA/QC and Verification

See the QA/QC and Verification section under *Land Converted to Grassland*.

Planned Improvements

Soil C stock changes with land use conversion from forest land to grassland are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and grasslands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to grassland. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.8 Wetlands Remaining Wetlands

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands which have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., clearing surface biomass, draining), extraction (which results in the emissions reported under *Peatlands Remaining Peatlands*), and abandonment, restoration, or conversion of the land to another use.

CO₂ emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH₄ and N₂O. The natural production of CH₄ is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al., 2004 as cited in IPCC 2006); however, CH₄ emissions are assumed to be insignificant under IPCC Tier 1 methodology (IPCC, 2006). N₂O emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions, and at present no methodology is provided by IPCC (2006) to estimate greenhouse gas emissions or removals from restored peatlands. This inventory estimates both CO₂ and N₂O emissions from *Peatlands Remaining Peatlands* in accordance with Tier 1 IPCC (2006) guidelines.

CO₂ and N₂O Emissions from Peatlands Remaining Peatlands

IPCC (2006) recommends reporting CO₂ and N₂O emissions from lands undergoing active peat extraction (i.e., *Peatlands Remaining Peatlands*) as part of the estimate for emissions from managed wetlands. Peatlands occur where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: sphagnum bogs in northern states and wetlands in states further south. The peat from sphagnum bogs in northern states, which is nutrient poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient rich.

IPCC (2006) recommends considering both on-site and off-site emissions when estimating CO₂ emissions from *Peatlands Remaining Peatlands* using the Tier 1 approach. Current methodologies estimate only on-site N₂O emissions, since off-site N₂O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat. On-site emissions from managed peatlands occur as the land is cleared of vegetation and the underlying peat is exposed to sun and weather. As this occurs, some peat deposit is lost and CO₂ is emitted from the oxidation of the peat. Since N₂O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N₂O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands located on highly fertile soils contain significant amounts of organic nitrogen in inactive form. Draining land in preparation for peat extraction allows bacteria to convert the nitrogen into nitrates which leach to the surface where they are reduced to N₂O.

Off-site CO₂ emissions from managed peatlands occur from the horticultural and landscaping use of peat. Nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most of the CO₂ emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for horticultural purposes.

Total emissions from *Peatlands Remaining Peatlands* were estimated to be 0.922 Tg CO₂ Eq. in 2011 (see Table 7-38) comprising 0.918 Tg CO₂ Eq. (918 Gg) of CO₂ and 0.004 Tg CO₂ Eq. (0.014 Gg) of N₂O. Total emissions in 2011 were about 9 percent smaller than total emissions in 2010, with the decrease due to the decrease in peat production reported in the lower 48 states in 2011. At the time of writing, peat production in Alaska (reported in cubic meters) was not yet published, and was therefore assumed to equal the value reported in 2010; although early indications were that production in 2011 will be slightly higher than in 2010 (Harbo 2012 as cited in USGS 2012).

Total emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.9 and 1.2 Tg CO₂ Eq. across the time series with a decreasing trend from 1990 until 1994 followed by an increasing trend through 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009, when the trend reversed. Emissions in 2011 represent a decline from emissions in 2010. CO₂ emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.9 and 1.2 Tg CO₂ across the time series, and these emissions drive the trends in total emissions. N₂O emissions remained close to zero across the time series, with a decreasing trend from 1990 until 1995 followed by an increasing trend through 2000. N₂O emissions decreased between 2000 and 2006, followed by a leveling off between 2008 and 2010, and a decline in 2011.

Table 7-38: Emissions from *Peatlands Remaining Peatlands* (Tg CO₂ Eq.)

Gas	1990	2005	2007	2008	2009	2010	2011
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CO ₂	1.0		1.1		1.0	1.0	1.1	1.0	0.9
N ₂ O	+		+		+	+	+	+	+
Total	1.0		1.1		1.0	1.0	1.1	1.0	0.9

+ Less than 0.05 Tg CO₂ Eq.

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports and stockpiles (i.e., apparent consumption).

Table 7-39: Emissions from *Peatlands Remaining Peatlands* (Gg)

Gas	1990		2005		2007	2008	2009	2010	2011
CO ₂	1,033		1,079		1,012	992	1,089	1,010	918
N ₂ O	+		+		+	+	+	+	+

+ Less than 0.5 Gg

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption).

Methodology

Off-Site CO₂ Emissions

CO₂ emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO₂ emissions from *Peatlands Remaining Peatlands* were calculated by apportioning the annual weight of peat produced in the United States (Table 7-40) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage-by-weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default C fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. For the lower 48 states, both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS 1991–2012). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. On average, about 75 percent of the peat operations respond to the survey. USGS estimated data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The Alaska estimates rely on reported peat production from Alaska’s annual Mineral Industry Reports (Szumigala et al. 2010). Similar to the U.S. Geological Survey, Alaska’s Mineral Industry Report methodology solicits voluntary reporting of peat production from producers. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the lower 48 states and Alaska, large variations in peat production can also result from variations in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production (USGS 1991–2012). The methodology estimates Alaska emissions separately from lower 48 emissions because the state conducts its own mineral survey and reports peat production by volume, rather than by weight (Table 7-41). However, volume production data were used to calculate off-site CO₂ emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).²⁴²

The *apparent consumption* of peat, which includes production plus imports minus exports plus the decrease in stockpiles, in the United States is over two-and-a-half times the amount of domestic peat production. Therefore, off-site CO₂ emissions from the use of all horticultural peat within the United States are not accounted for using the Tier 1 approach. The United States has increasingly imported peat from Canada for horticultural purposes; from 2007 to 2010, imports of sphagnum moss (nutrient-poor) peat from Canada represented 97 percent of total U.S. peat imports (USGS 2012a). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is

²⁴² Peat produced from Alaska was assumed to be nutrient poor; as is the case in Canada, “where deposits of high-quality [but nutrient poor] sphagnum moss are extensive” (USGS 2008).

classified as nutrient rich by IPCC (2006). Higher-tier calculations of CO₂ emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient rich versus nutrient poor) as well as the percentages of peat types imported and exported.

Table 7-40: Peat Production of Lower 48 States (in thousands of Metric Tons)

Type of Deposit	1990		2005		2007	2008	2009	2010	2011
Nutrient-Rich	595.1		657.6		581.0	559.7	560.3	558.9	511.2
Nutrient-Poor	55.4		27.4		54.0	55.4	48.7	69.1	56.8
Total Production	692.0		685.0		635.0	615.0	609.0	628.0	568.0

Sources: United States Geological Survey (USGS) (1991–2012) *Minerals Yearbook: Peat (1994–2011)*; United States Geological Survey (USGS) (1996–2012) *Mineral Commodity Summaries: Peat (1996–2011)*.

Table 7-41: Peat Production of Alaska (in thousands of Cubic Meters)

	1990		2005		2007	2008	2009	2010	2011
Total Production	49.7		47.8		52.3	64.1	183.9	59.8	59.8

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2011) *Alaska's Mineral Industry Report (1997–2010)*.

On-site CO₂ Emissions

IPCC (2006) suggests basing the calculation of on-site emissions estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of land managed for peat extraction is currently not available for the United States, but in accordance with IPCC (2006), an average production rate for the industry was applied to derive an area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006).²⁴³ The area of land managed for peat extraction in the United States was estimated using nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year. The annual land area estimates were then multiplied by the appropriate nutrient-rich or nutrient-poor IPCC (2006) default emission factor in order to calculate on-site CO₂ emission estimates. Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from *Peatlands Remaining Peatlands* in Alaska, the production data by volume were converted to weight using annual average bulk peat density values, and then converted to land area estimates using the same assumption that a single hectare yields 100 metric tons. The IPCC (2006) on-site emissions equation also includes a term which accounts for emissions resulting from the change in C stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in C stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006).

On-site N₂O Emissions

IPCC (2006) suggests basing the calculation of on-site N₂O emissions estimates on the area of nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site CO₂ emissions methodology above details the calculation of area data from production data. In order to estimate N₂O emissions, the area of nutrient rich *Peatlands Remaining Peatlands* was multiplied by the appropriate default emission factor taken from IPCC (2006).

²⁴³ The vacuum method is one type of extraction that annually “mills” or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

Uncertainty

The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed. The uncertainty associated with peat production data stems from the fact that the USGS receives data from the smaller peat producers but estimates production from some larger peat distributors. The peat type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution). The uncertainty associated with the Alaskan reported production data was assumed to be the same as the lower 48 states, or ± 25 percent with a normal distribution. It should be noted that the Alaska Department of Natural Resources estimates that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008). The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008). IPCC (2006) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emission factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed. The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed. Based on these values and distributions, a Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO₂ and N₂O emissions from *Peatlands Remaining Peatlands*. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-42. CO₂ emissions from *Peatlands Remaining Peatlands* in 2011 were estimated to be between 0.6 and 1.2 Tg CO₂ Eq. at the 95 percent confidence level. This indicates a range of 33 percent below to 35 percent above the 2011 emission estimate of 0.9 Tg CO₂ Eq. N₂O emissions from *Peatlands Remaining Peatlands* in 2011 were estimated to be between 0.001 and 0.006 Tg CO₂ Eq. at the 95 percent confidence level. This indicates a range of 74 percent below to 39 percent above the 2011 emission estimate of 0.004 Tg CO₂ Eq.

Table 7-42: Tier-2 Quantitative Uncertainty Estimates for CO₂ Emissions from *Peatlands Remaining Peatlands*

Source	Gas	2011 Emissions Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emissions Estimate ^a			
			(Tg CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining	CO ₂	0.9	0.6	1.2	-33%	35%
Peatlands	N ₂ O	+	+	+	-74%	39%

+ Does not exceed 0.01 Tg CO₂ Eq. or 0.5 Gg.

^a Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The current Inventory represents the fifth Inventory report in which emissions from *Peatlands Remaining Peatlands* are included. The Inventory estimates for 2010 have been updated to incorporate new information on the proportion of rich and poor peat soil, and the bulk density of peat types in 2010. These data are from the advance release of the *2010 Mineral Yearbook: Peat* (USGS 2012b), which was released too late to be fully incorporated into the previous Inventory estimates. Updating these 2010 input values resulted in an 8 percent decrease compared to the previous Inventory report's 2010 emission estimate.

Planned Improvements

In order to further improve estimates of CO₂ and N₂O emissions from *Peatlands Remaining Peatlands*, future efforts will consider options for obtaining better data on the quantity of peat harvested per hectare and the total area undergoing peat extraction.

7.9 Settlements Remaining Settlements

Changes in Carbon Stocks in Urban Trees (IPCC Source Category 5E1)

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). Urban areas (cities, towns, and villages) are estimated to cover over 3 percent of the United States (U.S. Census Bureau 2012). With an average tree canopy cover of 35 percent, urban areas account for approximately 5 percent of total tree cover in the continental United States (Nowak and Greenfield 2012). Trees in urban areas of the United States were estimated to account for an average annual net sequestration of 58.5 Tg CO₂ Eq. (16.0 Tg C) over the period from 1990 through 2011. Net C flux from urban trees in 2011 was estimated to be -68.8 Tg CO₂ Eq. (-18.8 Tg C). Annual estimates of CO₂ flux (Table 7-43) were developed based on periodic (1990, 2000, and 2010) U.S. Census data on urbanized area. The estimate of urbanized area is smaller than the area categorized as *Settlements* in the Representation of the U.S. Land Base developed for this report, by an average of 47 percent over the 1990 through 2011 time series—i.e., the Census urban area is a subset of the *Settlements* area.

In 2011, urban area was about 44 percent smaller than the total area defined as *Settlements*. Census area data are preferentially used to develop C flux estimates for this source category since these data are more applicable for use with the available peer-reviewed data on urban tree canopy cover and urban tree C sequestration. Annual sequestration increased by 45 percent between 1990 and 2011 due to increases in urban land area. Data on C storage and urban tree coverage were collected since the early 1990s and have been applied to the entire time series in this report. As a result, the estimates presented in this chapter are not truly representative of changes in C stocks in urban trees for *Settlements* areas, but are representative of changes in C stocks in urban trees for Census urban area. The method used in this report does not attempt to scale these estimates to the *Settlements* area. Therefore, the estimates presented in this chapter are likely an underestimate of the true changes in C stocks in urban trees in all *Settlements* areas—i.e., the changes in C stocks in urban trees presented in this chapter are a subset of the changes in C stocks in urban trees in all *Settlements* areas.

Net C flux from urban trees is proportionately greater on an area basis than that of forests. This trend is primarily the result of different net growth rates in urban areas versus forests—urban trees often grow faster than forest trees because of the relatively open structure of the urban forest (Nowak and Crane 2002). However, areas in each case are accounted for differently. Because urban areas contain less tree coverage than forest areas, the C storage per hectare of land is in fact smaller for urban areas. However, urban tree reporting occurs on a basis of C sequestered per unit area of tree cover, rather than C sequestered per total land area. Expressed per unit of tree cover, areas covered by urban trees have a greater C density than do forested areas (Nowak and Crane 2002). Expressed per unit of land area, however, the situation is the opposite: urban areas have a smaller C density than forest areas.

Table 7-43: Net C Flux from Urban Trees (Tg CO₂ Eq. and Tg C)

Year	Tg CO ₂ Eq.	Tg C
1990	(47.5)	(13.0)
2005	(63.2)	(17.2)
2007	(65.0)	(17.7)
2008	(66.0)	(18.0)
2009	(66.9)	(18.3)
2010	(67.9)	(18.5)

2011	(68.8)	(18.8)
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Note: Parentheses indicate net sequestration.

Methodology

Methods for quantifying urban tree biomass, C sequestration, and C emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013, in review), Nowak and Crane (2002), and Nowak (1994). In general, the methodology used by Nowak et al. (2013, in review) to estimate net C sequestration in urban trees followed three steps. First, field data from 28 cities were used to generate allometric estimates of biomass from measured tree dimensions. Second, estimates of tree growth and biomass increment were generated from published literature and adjusted for tree condition and land-use class to generate estimates of gross C sequestration in urban trees. Third, estimates of C emissions due to mortality and decomposition were subtracted from gross C sequestration values to derive estimates of net C sequestration. Finally, sequestration estimates for these cities, in units of C sequestered per unit area of tree cover, were used to estimate urban forest C sequestration in the U.S. by using urban area estimates from U.S. Census data and urban tree cover estimates from remote sensing data, an approach consistent with Nowak et al. (2013, in review).

This approach is also consistent with the default IPCC methodology in IPCC (2006), although sufficient data are not yet available to separately determine interannual gains and losses in C stocks in the living biomass of urban trees. Annual changes in net C flux from urban trees are based solely on changes in total urban area in the United States.

In order to generate the allometric relationships between tree dimensions and tree biomass, Nowak et al. (2013, in review) and previously published information (Nowak and Crane 2002; and Nowak 1994, 2007c, and 2009) collected field measurements in a number of U.S. cities between 1989 and 2012. For a sample of trees in each of the cities in Table 7-44, data including tree measurements of stem diameter, tree height, crown height and crown width, and information on location, species, and canopy condition were collected. The data for each tree were converted into C storage by applying allometric equations to estimate aboveground biomass, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, moisture content, a C content of 50 percent (dry weight basis), and an adjustment factor of 0.8 to account for urban trees having less aboveground biomass for a given stem diameter than predicted by allometric equations based on forest trees (Nowak 1994). C storage estimates for deciduous trees include only C stored in wood. These calculations were then used to develop an allometric equation relating tree dimensions to C storage for each species of tree, encompassing a range of diameters.

Tree growth was estimated using annual height growth and diameter growth rates for specific land uses and diameter classes. Growth calculations were adjusted by a factor to account for tree condition (fair to excellent, poor, critical, dying, or dead). For each tree, the difference in C storage estimates between year 1 and year (x + 1) represents the gross amount of C sequestered. These annual gross C sequestration rates for each species (or genus), diameter class, and land-use condition (e.g., parks, transportation, vacant, golf courses) were then scaled up to city estimates using tree population information. The area of assessment for each city was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates (Nowak 2011).

Most of the field data used to develop the methodology of Nowak et al. (2013, in review) were analyzed using the U.S. Forest Service's Urban Forest Effects (UFORE) model. UFORE is a computer model that uses standardized field data from random plots in each city and local air pollution and meteorological data to quantify urban forest structure, values of the urban forest, and environmental effects, including total C stored and annual C sequestration. UFORE was used with field data from a stratified random sample of plots in each city to quantify the characteristics of the urban forest. (Nowak et al. 2007a).

Gross C emissions result from tree death and removals. Estimates of gross C emissions from urban trees were derived by applying estimates of annual mortality and condition, and assumptions about whether dead trees were removed from the site to the total C stock estimate for each city. Estimates of annual mortality rates by diameter class and condition class were derived from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass. The estimated annual gross C emission rates for each species (or genus), diameter class, and condition class were then scaled up to city estimates using tree population information.

The field data for the 28 cities are described in Nowak et al. (2013, in review), which builds upon previous research, including: Nowak and Crane (2002), Nowak et al. (2007a), and references cited therein. The allometric equations applied to the field data for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric equation could be found for the particular species, the average result for the genus was used. The adjustment (0.8) to account for less live tree biomass in urban trees was based on information in Nowak (1994). Measured tree growth rates for street (Frelich 1992; Fleming 1988; Nowak 1994), park (deVries 1987), and forest (Smith and Shifley 1984) trees were standardized to an average length of growing season (153 frost free days) and adjusted for site competition and tree condition. Standardized growth rates of trees of the same species or genus were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Crown light exposure (CLE) measurements (number of sides and/or top of tree exposed to sunlight) were used to represent forest, park, and open (street) tree growth conditions. Local tree base growth rates (BG) were then calculated as the average standardized growth rate for open-grown trees multiplied by the number of frost free days divided by 153. Growth rates were then adjusted for CLE. The CLE adjusted growth rate was then adjusted based on tree health and tree condition to determine the final growth rate. Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak et al. 2013, in review).

Estimates of gross and net sequestration rates for each of the 28 cities (Table 7-44) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of national urban area and urban tree cover data to calculate national annual net C sequestration by urban trees for the United States. This method was described in Nowak et al. (2013, in review) and has been modified to incorporate U.S. Census data.

Specifically, urban area estimates were based on 1990, 2000, and 2010 U.S. Census data. The 1990 U.S. Census defined urban land as “urbanized areas,” which included land with a population density greater than 1,000 people per square mile, and adjacent “urban places,” which had predefined political boundaries and a population total greater than 2,500. In 2000, the U.S. Census replaced the “urban places” category with a new category of urban land called an “urban cluster,” which included areas with more than 500 people per square mile. In 2010, the Census updated its definitions to have “urban areas” encompassing Census tract delineated cities with 50,000 or more people, and “urban clusters” containing Census tract delineated locations with between 2,500 and 50,000 people. Urban land area increased by approximately 23 percent from 1990 to 2000 and 16 percent from 2000 to 2010; Nowak et al. (2005) estimate that the changes in the definition of urban land are responsible for approximately 20 percent of the total reported increase in urban land area from 1990 to 2000. Under all Census (i.e., 1990, 2000, and 2010) definitions, the urban category encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). *Settlements* area, as assessed in the Representation of the U.S. Land Base developed for this report, encompassed all developed parcels greater than 0.1 hectares in size, including rural transportation corridors, and as previously mentioned represents a larger area than the Census-derived urban area estimates. However, the smaller, Census-derived urban area estimates were deemed to be more suitable for estimating national urban tree cover given the data available in the peer-reviewed literature (i.e., the data set available is consistent with Census urban rather than *Settlements* areas), and the recognized overlap in the changes in C stocks between urban forest and non-urban forest (see Planned Improvements below). Specifically, tree canopy cover of U.S. urban areas was estimated by Nowak and Greenfield (2012) to be 35 percent, assessed across Census-delineated urbanized areas and urban clusters. This canopy cover percentage is multiplied by the urban area estimated for each year to produce an estimate of national urban tree cover area.

Net annual C sequestration estimates were derived for the 28 cities by subtracting the gross annual emission estimates from the gross annual sequestration estimates. The gross and net annual C sequestration values for each city were divided by each city’s area of tree cover to determine the average annual sequestration rates per unit of tree area for each city. The median value for gross sequestration per unit area of tree cover ($0.26 \text{ kg C/m}^2\text{-yr}$) was then multiplied by the estimate of national urban tree cover area to estimate national annual gross sequestration, per the methods of Nowak et al. (2013, in review). To estimate national annual net sequestration, the estimate of national annual gross sequestration was multiplied by the average of the ratios of net to gross sequestration (0.72) for those cities that had both estimates. The urban tree cover estimates for each of the 28 cities and the United States were obtained from Nowak et al. (2013, in review) which compiled ten years of research including Dwyer et al. (2000), Nowak et al. (2002), Nowak (2007a), and Nowak (2009). The urban area estimates were taken from the 2010 U.S. Census (2012).

Table 7-44: C Stocks (Metric Tons C), Annual C Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m²-yr) for 28 U.S. Cities

City	Carbon Stocks	Gross Annual Sequestration	Net Annual Sequestration	Tree Cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover	Net:Gross Annual Sequestration Ratio
Arlington, TX	1,682,599	15,528	14,126	22.5	0.288	0.262	0.91
Atlanta, GA	2,263,366	38,227	29,213	53.9	0.229	0.175	0.76
Baltimore, MD	1,832,289	15,251	9,086	28.5	0.282	0.168	0.60
Boston, MA	1,002,364	8,648	6,289	28.9	0.231	0.168	0.73
Casper, WY	380,972	975	525	8.9	0.221	0.119	0.54
Chicago, IL	3,606,103	20,703	14,551	18.0	0.212	0.149	0.70
Freehold, NJ	58,074	449	287	31.2	0.314	0.201	0.64
Gainesville, FL	770,597	12,294	8,941	50.6	0.220	0.160	0.73
Golden, CO	143,880	577	458	11.4	0.228	0.181	0.79
Jersey City, NJ	496,573	3,566	2,016	26.2	0.329	0.186	0.57
Hartford, CT	167,630	732	528	11.5	0.183	0.132	0.72
Lincoln, NE	2,021,556	10,152	8,712	14.4	0.409	0.351	0.86
Los Angeles, CA	5,589,259	40,052	24,350	20.6	0.176	0.107	0.61
Milwaukee, WI	1,819,099	12,766	8,740	21.6	0.260	0.178	0.68
Minneapolis, MN	666,381	7,339	3,786	34.1	0.157	0.081	0.52
Moorestown, NJ	378,291	3,090	2,327	28.0	0.320	0.241	0.75
Morgantown, WV	212,767	2,385	1,855	39.6	0.297	0.231	0.78
New York, NY	5,858,668	34,856	18,792	20.9	0.230	0.124	0.54
Omaha, NE	4,223,950	20,576	16,084	14.8	0.513	0.401	0.78
Philadelphia, PA	2,312,040	13,275	9,731	20.8	0.206	0.151	0.73
Roanoke, VI	1,019,062	12,710	8,537	31.7	0.399	0.268	0.67
Sacramento, CA	10,219,814	59,001	51,176	13.2	0.377	0.327	0.87
San Francisco, CA	1,100,474	4,194	3,846	16.0	0.241	0.221	0.92
Scranton, PA	384,930	3,317	2,461	22.0	0.399	0.296	0.74
Syracuse, NY	558,424	4,521	3,205	26.9	0.285	0.202	0.71
Washington, DC	1,355,928	13,290	10,561	35.0	0.263	0.209	0.79
Woodbridge, NJ	491,062	4,573	3,338	29.5	0.285	0.208	0.73
					Median: 0.26		Mean: 0.72

NA = not analyzed.

Sources: Nowak et al. (2013, in review)

Uncertainty and Time-Series Consistency

Uncertainty associated with changes in C stocks in urban trees includes the uncertainty associated with urban area, percent urban tree coverage, and estimates of gross and net C sequestration for each of the 28 U.S. cities. A 10 percent uncertainty was associated with urban area estimates based on expert judgment, while a 1.4 percent uncertainty is reported for the percent urban tree coverage value (Nowak and Greenfield 2012). Uncertainty associated with estimates of gross and net C sequestration for each of the 28 U.S. cities was based on standard error estimates for each of the city-level sequestration estimates reported by Nowak et al (2013, in review). These estimates are based on field data collected in each of the 28 U.S. cities, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass equations, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil C stocks, and there may be some overlap between the urban tree C estimates and the forest tree C estimates. Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of urban tree and forest tree estimates will be addressed through the land-representation effort described in the Planned Improvements section of this chapter.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-45. The net C flux from changes in C stocks in urban trees in 2011 was estimated to be between -81.9 and -59.9 Tg CO₂ Eq. at a 95 percent confidence level. This indicates a range of 19 percent more sequestration to 13 percent less sequestration than the 2011 flux estimate of -68.8 Tg CO₂ Eq.

Table 7-45: Tier 2 Quantitative Uncertainty Estimates for Net C Flux from Changes in C Stocks in Urban Trees (Tg CO₂ Eq. and Percent)

Source	Gas	2011 Flux Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO ₂ Eq.)			
			Lower Bound	Upper Bound	Lower Bound (%)	Upper Bound (%)
Changes in C Stocks in Urban Trees	CO ₂	(68.8)	(81.9)	(59.9)	19%	-13%

Note: Parentheses indicate negative values or net sequestration.

Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

The net C flux resulting from urban trees was predominately calculated using city-specific estimates of gross and net C sequestration estimates for urban trees and urban tree coverage area published in the literature. The validity of these data for their use in this section of the inventory was evaluated through correspondence established with Dr. David J. Nowak, an author of the papers. Through this correspondence, the methods used to collect the urban tree sequestration and area data were further clarified and the use of these data in the inventory was reviewed and validated (Nowak 2002a, 2007b, 2011, and Nowak et al. 2013 in review).

Recalculations

The 1990 to 2010 net C flux estimates were recalculated relative to the previous Inventory based on three changes in activity data; (1) 2010 U.S. Census data were released in March 2012, along with updated definitions of urban area and urban cluster, resulting in revisions to the annual urban area estimated for 1990 to 2010; (2) a revised average urban tree canopy cover (35.0 percent) was published by Nowak and Greenfield (2012); and (3) C sequestration data was available for 28 rather than 14 cities from Nowak et al. (2013, in review). The combination of the methodological and historical data changes resulted in an average annual net sequestration decrease of 19.5 Tg CO₂ Eq. (24.5 percent) in urban trees compared to the previous report across the entire time-series.

Planned Improvements

A consistent representation of the managed land base in the United States is discussed at the beginning of the *Land Use, Land-Use Change, and Forestry* chapter, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between urban forest and non-urban forest greenhouse gas inventories. Urban forest inventories are including areas also defined as forest land under the Forest Inventory and Analysis (FIA) program of the USDA Forest Service, resulting in “double-counting” of these land areas in estimates of C stocks and fluxes for this report. For example, Nowak et al. (2013, in review) estimates that 13.7 percent of urban land is measured by the forest inventory plots, and could be responsible for up to 87 Tg C of overlap.

Urban tree cover data specific to all 50 states has been developed (Nowak 2013, in review). It may be possible to develop and use a set of state-specific sequestration rates for estimating regional C flux estimates.

Future research may also enable more complete coverage of changes in the C stock in urban trees for all Settlements land. To provide estimates for all Settlements, research would need to establish the extent of overlap between Settlements and Census-defined urban areas, and would have to characterize sequestration on non-urban Settlements land.

Direct N₂O Fluxes from Settlement Soils (IPCC Source Category 5E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 2.4 percent are currently applied to lawns, golf courses, and other landscaping occurring within settlement areas. Application rates are lower than those occurring on cropped soils, and, therefore, account for a smaller proportion of total U.S. soil N₂O emissions per unit area. In addition to synthetic N fertilizers, a portion of surface applied sewage sludge is applied to settlement areas. In 2011, N₂O emissions from settlement soils were 1.5 Tg CO₂ Eq. (4.8 Gg). There was an overall increase of 51 percent over the period from 1990 through 2011 due to a general increase in the application of synthetic N fertilizers to an expanding settlement area. Interannual variability in these emissions is directly attributable to interannual variability in total synthetic fertilizer consumption and sewage sludge applications in the United States. Emissions from this source are summarized in Table 7-46.

Table 7-46: Direct N₂O Fluxes from Soils in *Settlements Remaining Settlements* (Tg CO₂ Eq. and Gg N₂O)

Year	Tg CO ₂ Eq.	Gg
1990	1.0	3.2
2005	1.5	4.7
2007	1.6	5.1
2008	1.5	4.7
2009	1.4	4.5
2010	1.5	4.7
2011	1.5	4.8

Note: These estimates include direct N₂O emissions from N fertilizer additions only. Indirect N₂O emissions from fertilizer additions are reported in the Agriculture chapter. These estimates include emissions from both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

Methodology

For soils within *Settlements Remaining Settlements*, the IPCC Tier 1 approach was used to estimate soil N₂O emissions from synthetic N fertilizer and sewage sludge additions. Estimates of direct N₂O emissions from soils in settlements were based on the amount of N in synthetic commercial fertilizers applied to settlement soils, and the amount of N in sewage sludge applied to non-agricultural land and surface disposal of sewage sludge (see Annex 3.11 for a detailed discussion of the methodology for estimating sewage sludge application).

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Ruddy et al. 2006). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1982 through 2001 (Ruddy et al. 2006). Non-farm N fertilizer was assumed to be applied to settlements and forest lands; values for 2002 through 2008 were based on 2001 values adjusted for annual total N fertilizer sales in the United States because there is no new activity data on application after 2001. Settlement application was calculated by subtracting forest application from total non-farm fertilizer use. Sewage sludge applications were derived from national data on sewage sludge generation, disposition, and N content (see Annex 3.11 for further detail). The total amount of N resulting from these sources was multiplied by the IPCC default emission factor for applied N (1 percent) to estimate direct N₂O emissions (IPCC 2006). The volatilized and leached/runoff N fractions for settlements, calculated with the IPCC default volatilization factors (10 or 20 percent, respectively, for synthetic or organic N fertilizers) and leaching/runoff factor for wet areas (30 percent), were included with indirect emissions, as reported in the N₂O Emissions from Agricultural Soil Management source category of the Agriculture chapter (consistent

with reporting guidance that all indirect emissions are included in the Agricultural Soil Management source category).

Uncertainty and Time-Series Consistency

The amount of N₂O emitted from settlements depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and irrigation/watering practices. The effect of the combined interaction of these variables on N₂O flux is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate any of these variables, except variations in fertilizer N and sewage sludge application rates. All settlement soils are treated equivalently under this methodology.

Uncertainties exist in both the fertilizer N and sewage sludge application rates in addition to the emission factors. Uncertainty in fertilizer N application was assigned a default level of ± 50 percent.²⁴⁴ Uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal was derived from variability in several factors, including: (1) N content of sewage sludge; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the sewage sludge disposal practice distributions to non-agricultural land application and surface disposal. Uncertainty in the emission factors was provided by the IPCC (2006).

Quantitative uncertainty of this source category was estimated through the IPCC-recommended Tier 2 uncertainty estimation methodology. The uncertainty ranges around the 2005 activity data and emission factor input variables were directly applied to the 2011 emission estimates. The results of the quantitative uncertainty analysis are summarized in Table 7-47. N₂O emissions from soils in Settlements Remaining Settlements in 2011 were estimated to be between 0.8 and 3.9 Tg CO₂ Eq. at a 95 percent confidence level. This indicates a range of 49 percent below to 163 percent above the 2011 emission estimate of 1.5 Tg CO₂ Eq.

Table 7-47: Quantitative Uncertainty Estimates of N₂O Emissions from Soils in *Settlements Remaining Settlements* (Tg CO₂ Eq. and Percent)

Source	Gas	2011 Emissions (Tg CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO ₂ Eq.)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements: N ₂ O Fluxes from Soils	N ₂ O	1.5	0.8	3.9	-49%	163%

Note: This estimate includes direct N₂O emissions from N fertilizer additions to both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

Planned Improvements

A minor improvement is planned to update the uncertainty analysis for direct emissions from settlements to be consistent with the most recent activity data for this source.

²⁴⁴ No uncertainty is provided with the USGS fertilizer consumption data (Ruddy et al. 2006) so a conservative ± 50 % was used in the analysis.

7.10 Land Converted to Settlements (Source Category 5E2)

Land-use change is constantly occurring, and land under a number of uses undergoes urbanization in the United States each year. However, data on the amount of land converted to settlements is currently lacking. Given the lack of available information relevant to this particular IPCC source category, it is not possible to separate CO₂ or N₂O fluxes on *Land Converted to Settlements* from fluxes on *Settlements Remaining Settlements* at this time.

7.11 Other (IPCC Source Category 5G)

Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are discarded in landfills. Carbon contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon storage estimates are associated with particular land uses. For example, harvested wood products are accounted for under *Forest Land Remaining Forest Land* because these wood products are considered a component of the forest ecosystem. The wood products serve as reservoirs to which C resulting from photosynthesis in trees is transferred, but the removals in this case occur in the forest. Carbon stock changes in yard trimmings and food scraps are associated with settlements, but removals in this case do not occur within settlements. To address this complexity, yard trimming and food scrap C storage is reported under the “Other” source category.

Both the amount of yard trimmings collected annually and the fraction that is landfilled have declined over the last decade. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps were generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2011; Schneider 2007, 2008). Since then, programs banning or discouraging yard trimmings disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent 5 percent decrease in the tonnage generated (i.e., collected for composting or disposal). At the same time, an increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills—from 72 percent in 1990 to 35 percent in 2011. The net effect of the reduction in generation and the increase in composting is a 54 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990.

Food scrap generation has grown by 46 percent since 1990, and though the proportion of food scraps discarded in landfills has decreased slightly from 82 percent in 1990 to 80 percent in 2011, the tonnage disposed of in landfills has increased considerably (by 42 percent). Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in annual landfill C storage from 24.2 Tg CO₂ Eq. in 1990 to 13.0 Tg CO₂ Eq. in 2011 (Table 7-48 and Table 7-49).

Table 7-48: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg CO₂ Eq.)

Carbon Pool	1990		2005		2007	2008	2009	2010	2011
Yard Trimmings	(21.0)		(7.3)		(7.0)	(7.0)	(8.5)	(9.3)	(9.2)
Grass	(1.8)		(0.6)		(0.6)	(0.6)	(0.8)	(0.9)	(0.9)
Leaves	(9.0)		(3.3)		(3.2)	(3.2)	(3.9)	(4.2)	(4.2)
Branches	(10.2)		(3.4)		(3.2)	(3.1)	(3.8)	(4.1)	(4.1)
Food Scraps	(3.2)		(4.3)		(3.9)	(3.9)	(4.2)	(4.1)	(3.8)
Total Net Flux	(24.2)		(11.6)		(10.9)	(10.9)	(12.7)	(13.3)	(13.0)

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values

Table 7-49: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg C)

Carbon Pool	1990	2005	2007	2008	2009	2010	2011
Yard Trimmings	(5.7)	(2.0)	(1.9)	(1.9)	(2.3)	(2.5)	(2.5)
Grass	(0.5)	(0.2)	(0.2)	(0.2)	(0.2)	(0.3)	(0.2)
Leaves	(2.5)	(0.9)	(0.9)	(0.9)	(1.1)	(1.1)	(1.1)
Branches	(2.8)	(0.9)	(0.9)	(0.9)	(1.0)	(1.1)	(1.1)
Food Scraps	(0.9)	(1.2)	(1.1)	(1.1)	(1.1)	(1.1)	(1.0)
Total Net Flux	(6.6)	(3.2)	(3.0)	(3.0)	(3.5)	(3.6)	(3.6)

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values

Methodology

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the C that remains is effectively removed from the global C cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008; De la Cruz and Barlaz 2010), and thus the stock of C in landfills can increase, with the net effect being a net atmospheric removal of C. Estimates of net C flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled C stocks between inventory years, based on methodologies presented for the *Land Use, Land-Use Change, and Forestry* sector in IPCC (2003). Carbon stock estimates were calculated by determining the mass of landfilled C resulting from yard trimmings or food scraps discarded in a given year; adding the accumulated landfilled C from previous years; and subtracting the mass of C that was landfilled in previous years that decomposed.

To determine the total landfilled C stocks for a given year, the following were estimated: (1) the composition of the yard trimmings; (2) the mass of yard trimmings and food scraps discarded in landfills; (3) the C storage factor of the landfilled yard trimmings and food scraps; and (4) the rate of decomposition of the degradable C. The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted C storage factor (i.e., moisture content and C content) and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2010* (EPA 2011), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, and 2007 through 2010. Data were not yet published for 2011, consequently, 2011 data on discards for yard trimmings and food scraps were assumed to be equal to 2010 data from EPA (2011). To provide data for some of the missing years, detailed backup data were obtained from Schneider (2007, 2008). Remaining years in the time series for which data were not provided were estimated using linear interpolation. The EPA (2011) report does not subdivide discards of individual materials into volumes landfilled and combusted, although it provides an estimate of the proportion of overall waste stream discards managed in landfills²⁴⁵ and combustors with energy recovery (i.e., ranging from 100 percent and 0 percent, respectively, in 1960 to 81 percent and 19 percent in 2000); it is assumed that the proportion of each individual material (food scraps, grass, leaves, branches) that is landfilled is the same as the proportion across the overall waste stream.

The amount of C disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying by the initial (i.e., pre-decomposition) C content (as a fraction of dry weight). The dry weight of landfilled material was

²⁴⁵ EPA (2011) reports discards in two categories: “combustion with energy recovery” and “landfill, other disposal,” which includes combustion without energy recovery. For years in which there is data from previous EPA reports on combustion without energy recovery, EPA assumes these estimates are still applicable. For 2000 to present, EPA assumes that any combustion of MSW that occurs includes energy recovery, so all discards to “landfill, other disposal” are assumed to go to landfills.

calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 7-50).

The amount of C remaining in the landfill for each subsequent year was tracked based on a simple model of C fate. As demonstrated by Barlaz (1998, 2005, 2008), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment. Barlaz (1998, 2005, 2008) conducted a series of experiments designed to measure biodegradation of yard trimmings, food scraps, and other materials, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). After measuring the initial C content, the materials were placed in sealed containers along with methanogenic microbes from a landfill. Once decomposition was complete, the yard trimmings and food scraps were re-analyzed for C content; the C remaining in the solid sample can be expressed as a proportion of initial C (shown in the row labeled “CS, proportion of initial C stored (%)” in Table 7-50).

The modeling approach applied to simulate U.S. landfill C flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of C stored is assumed to persist in landfills. The remaining portion is assumed to degrade over time, resulting in emissions of CH₄ and CO₂ (the CH₄ emissions resulting from decomposition of yard trimmings and food scraps are accounted for in the *Waste* chapter). The degradable portion of the C is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 7-50.

The first-order decay rates, k , for each component were derived from De la Cruz and Barlaz (2010). De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, f , is found so that the weighted average decay rate for all components is equal to the AP-42 default decay rate (0.04) for mixed MSW for regions that receive more than 25 inches of rain annually. Because AP-42 values were developed using landfill data from approximately 1990, 1990 waste composition for the United States from EPA’s *Characterization of Municipal Solid Waste in the United States: 1990 Update* was used to calculate f . This correction factor is then multiplied by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are found, including dry conditions (less than 25 inches of rain annually, $k=0.02$) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, $k=0.12$). The *Landfills* section of the Inventory (which estimates CH₄ emissions) estimates the overall MSW decay rate by partitioning the U.S. landfill population into three categories, based on annual precipitation ranges of: (1) less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 year⁻¹, respectively.

De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 year⁻¹), but not for the other two overall MSW decay rates. To maintain consistency between landfill methodologies across the Inventory, the correction factors (f) were developed for decay rates of 0.038 and 0.057 year⁻¹ through linear interpolation. A weighted national average component-specific decay rate was calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The component-specific decay rates are shown in Table 7-50.

For each of the four materials (grass, leaves, branches, food scraps), the stock of C in landfills for any given year is calculated according to the following formula:

$$LFC_{i,t} = \sum_n^t W_{i,n} \times (1 - MC_i) \times ICC_i \times \{ [CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t-n)}] \}$$

where,

t	=	Year for which C stocks are being estimated (year),
i	=	Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$	=	Stock of C in landfills in year t , for waste i (metric tons),
$W_{i,n}$	=	Mass of waste i disposed of in landfills in year n (metric tons, wet weight),
n	=	Year in which the waste was disposed of (year, where $1960 < n < t$),
MC_i	=	Moisture content of waste i (percent of water),
CS_i	=	Proportion of initial C that is stored for waste i (percent),

ICC_i	=	Initial C content of waste i (percent),
e	=	Natural logarithm, and
k	=	First-order decay rate for waste i , (year ⁻¹).

For a given year t , the total stock of C in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of C in landfills (F_t) for year t is calculated as the change in stock compared to the preceding year:

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, the C placed in a landfill in year n is tracked for each year t through the end of the inventory period (2011). For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (518,000 metric tons) decomposes, leaving a total of 617,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2011, the total food scraps C originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed of in subsequent years (1961 through 2011), the total landfill C from food scraps in 2011 was 38.1 million metric tons. This value is then added to the C stock from grass, leaves, and branches to calculate the total landfill C stock in 2011, yielding a value of 254.2 million metric tons (as shown in Table 7-51). In exactly the same way total net flux is calculated for forest C and harvested wood products, the total net flux of landfill C for yard trimmings and food scraps for a given year (Table 7-49) is the difference in the landfill C stock for that year and the stock in the preceding year. For example, the net change in 2011 shown in Table 7-49 (3.6 Tg C) is equal to the stock in 2011 (254.2 Tg C) minus the stock in 2010 (250.7 Tg C).

The C stocks calculated through this procedure are shown in Table 7-51.

Table 7-50: Moisture Content (%), C Storage Factor, Proportion of Initial C Sequestered (%), Initial C Content (%), and Decay Rate (year⁻¹) for Landfilled Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H ₂ O)	70	30	10	70
CS, proportion of initial C stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate (year ⁻¹)	0.323	0.185	0.016	0.156

Table 7-51: C Stocks in Yard Trimmings and Food Scraps in Landfills (Tg C)

Carbon Pool	1990	2005	2007	2008	2009	2010	2011
Yard Trimmings	155.8	202.9	206.9	208.8	211.1	213.6	216.2
Branches	74.6	97.5	99.3	100.2	101.2	102.3	103.5
Leaves	66.7	87.3	89.2	90.0	91.1	92.2	93.4
Grass	14.5	18.1	18.4	18.6	18.8	19.0	19.3
Food Scraps	21.3	31.7	33.7	34.8	35.9	37.0	38.1
Total Carbon Stocks	177.2	234.7	240.6	243.6	247.0	250.7	254.2

Note: Totals may not sum due to independent rounding.

Uncertainty and Time-Series Consistency

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of C), initial C content, moisture

content, decay rate, and proportion of C stored. The C storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-52. Total yard trimmings and food scraps CO₂ flux in 2011 was estimated to be between –19.6 and –5.3 Tg CO₂ Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of 50 percent below to 59 percent above the 2011 flux estimate of –13.0 Tg CO₂ Eq. More information on the uncertainty estimates for Yard Trimmings and Food Scraps in Landfills is contained within the Uncertainty Annex.

Table 7-52: Tier 2 Quantitative Uncertainty Estimates for CO₂ Flux from Yard Trimmings and Food Scraps in Landfills (Tg CO₂ Eq. and Percent)

Source	Gas	2011 Flux Estimate (Tg CO ₂ Eq.)	Uncertainty Range Relative to Flux Estimate ^a			
			(Tg CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO ₂	(13.0)	(19.6)	(5.3)	–50%	+59%

^a Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Parentheses indicate negative values or net C sequestration.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2011. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

The current Inventory has been revised relative to the previous report. Input data were not yet published for 2011 at the time of writing, so *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Tables and Figures for 2010* (EPA 2011) input data were used for 2011. Although the input data were the same from 2010 to 2011, the final C stock and C flux estimates changed because of the decomposition model (see Methodology for more information regarding the decomposition model), which calculates the C that remains from yard trimmings and food scraps that were landfilled in past years.

Planned Improvements

Future work is planned to evaluate the consistency between the estimates of C storage described in this chapter and the estimates of landfill CH₄ emissions described in the *Waste* chapter. For example, the *Waste* chapter does not distinguish landfill CH₄ emissions from yard trimmings and food scraps separately from landfill CH₄ emissions from total bulk (i.e., municipal solid) waste, which includes yard trimmings and food scraps.